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INTRODUCTION

Most current research on optical fibers has so far been on topics such as the fiber material, scattering and absorption losses, mode characterization of various fiber configuration, mode control and dispersion. These factors concern linear transmission of light. Nonlinear effect in such fibers is of importance since it makes possible the operation of nonlinear optical devices at power levels much lower than those required for bulk media. In a negative sense, it can also present severe limitations to the amount of light that can be transmitted through a fiber. It has been shown that nonlinear effects can become significant and distort transmission in fibers at power levels on the order of milliwatts.

The nonlinear processes increase in importance with increasing I X L, the product of optical intensity and the interaction length (the so-called pumping factor we use in our work is the product of the incident pump power, the interaction length and the coupling coefficients[1]. In bulk media (without waveguiding), the intensity can be raised by focusing strongly but at the expense of the interaction length since the extent of the focal region decreases proportionately. Thus, for a given incident optical power P the product I X L remains constant:

$$I \times L = (P/\pi w_o^2) \times (\pi w_o^2/\lambda) = P/\lambda,$$

where w_o is the beam radius at the focus and Gaussian beam diffraction has been assumed, By using an optical fiber a focused intensity can be maintained over the length of the fiber with $I \times L = P(L/\pi w_o^2)$, where w_o is approximately the core radius of the fiber and L is the fiber length. In practice, fiber loss limits the effective interaction length so that

$$I \times L_{eff} = \int_o^L (P/\pi w_o^2) \exp(-\alpha z)\, dz = (P/\pi w_o^2) \times [1 - \exp(-\alpha z)]/\alpha,$$

where α is the linear loss coefficient of the fiber. Thus, the effective interaction length is $L_{eff} = [1 - \exp(-\alpha z)]/\alpha$, which simplifies to $L_{eff} = 1/\alpha$ for a sufficiently long fiber. Hence, in an optical fiber the intensity-length product can be enhanced by a factor of $(\lambda/\pi w_o^2) \times (1/\alpha)$, which is typically equivalent to a nonlinear enhancement of the order of 10^7 in the visible region. Nonlinear phenomena that used to require megawatts of laser power for observation can now take place in fibers at power levels in the watt range or less.

We are interested first in the natural nonlinear processes in fibers that lead to frequency conversion. These are stimulated Raman scattering (SRS) and stimulated Brillouin Scattering (SBS).

Attention so far has been focused on the stimulated processes where the gain coefficient is of main concern. We have carried out analysis where attention is given to the pump transmission and reflection characteristics. In this approach pump depletion is of primary importance, and is well suited to laser attenuation analysis since loss of light is the principal obstacle in earlier fiber development. We are thus proposing that there are two causes for the degradation of laser light transmission in optical fibers. One is the linear loss, which is being drastically reduced through enhanced fabrication techniques and search of better materials. However, the second and more important cause of degradation is due to nonlinear processes which are inherent and, as we shall see, low linear losses may even enhance these processes.

The SRS process is particularly suited to fiber geometry as it is nondirectional and automatically phase matched. A broad band of pump frequencies can provide gain for a single Stokes frequency. This simulates closely the situation where multiple pumps can act on a single signal wave.[7]

The Brillouin process is scattering of light by acoustic phonons in a material. Because of the flat dispersion relation $\omega(k) = \text{const.}$ for optical phonons near the center of the Brillouin zone, Raman scattering is isotropic and exhibits the same Stokes shift for all scattering directions. On the other hand, the linear dispersion relation $\omega = k \cdot v_s$, where v_s is the acoustic velocity, for the acoustic phonons introduces an angular dependence to the scattered frequency and eliminates scattering in the forward direction. Thus, in an optical fiber, SBS occurs only in the backward direction. For visible light the frequency shift of the light is on the order of 30 GHz in glasses.

SBS has been observed to deplete a transmitted laser pulse. There is also experimental evidence of the possibility of a backward SBS pulse to attain a peak power greatly exceeding that of the input pulse. A short pulse traveling in the backward direction can sweep out (and compress in time) the energy of a longer pump pulse in the fiber. When the power in such a pulse becomes high enough, permanent damage to the fiber can result.

We intend to carry out a detailed experimental and theoretical study of the laser pump depletion characteristics in an optical fiber due to SRS and SBS and possible SBS induced fiber damage. Possible laser beam self-focusing due to the focused Gaussian beam profile and radially graded refractive index of fibers now in use will be carefully explored. The measurement techniques used will be quite similar to those we have used on bulk materials.[8]

It has been predicted that at low power densities, the losses of an optical fiber should be determined by spontaneous Raman, Brillouin, and Rayleigh scattering, absorption losses in the bulk material, scattering at the core-cladding interface and mode conversion from low-loss trapped modes to high-loss cladding modes. At high power densities, the stimulated scattering processes take place within the fiber and these are power dependent. Backward-wave type stimulated scattering

processes such as Raman and Brillouin will thus convert power in the forward-traveling, information carrying wave into backward-traveling waves and thus attenuate severely the forward-traveling wave.

Stimulated Raman scattering can be either forward or backward wave while stimulated Brillouin scattering is strictly a backward wave in amorphous media such as glass. In the assumption of absence of pump depletion, stimulated Brillouin scattering should determine the maximum power handling capacity of a fiber. It is estimated to occur at a power level of 35 mW.[2] The critical power is approximately two orders higher for stimulated Raman scattering.

We have thus first concluded that we would only study the stimulated Brillouin process involving scattering of light by acoustic phonons in the material. The SBS threshold has been estimated to be less than 10 mW.

A lower pump threshold is not the only factor in determining the onset of a stimulated process. Another factor is the linewidth of the pump. In the forward scattering case, multiple pumps separated by more than the Raman linewidth can provide gain for a single Stokes wave because all pumps drive the same phonons. Backward wave as in stimulated Brillouin scattering needs phase matching that eliminates this possibility. Thus, in SBS only pump frequencies within a band equal to the linewidth provide gain for a single Stokes wave. SRS is favored if the laser pump linewidth exceeds the Brillouin linewidth by a multiple greater than the ratio of SBS gain to SRS gain. Efficient SBS requires narrowing the pump laser linewidth to about 100 MHz.

We propose to study the effect of stimulated Brillouin and Raman scattering on the power handling capacity and transmission characteristics of optical fibers as these scattering processes are predicted to be of prime importance in the case of no loss (ideal case)[1] and low loss[2] fibers. A critical power threshold exists for both forward and backward Raman and backward Brillouin scattering. We must

emphasize the distinction between the effects of forward and backward scattering. In the case of stimulated forward scattering, power of the fundamental radiation is transferred to the Raman components which still propagate in the forward direction as the fundamental pump radiation. On the other hand, in backward stimulated scattering, the Raman or Brillouin components after having derived their power from the fundamental pump propagate backwards so that they do not form part of the forward transmitted beam, that is, they are not part of the laser throughput.

These effects have been analyzed in Ref. 2 without taking into account pump depletion. Such an approach is valid when used to establish thresholds for the onset of these processes. However, it is not applicable to the description of the transmission characteristics of the fundamental pump radiation beyond the threshold. Furthermore, the threshold established there is based on balancing linear loss with the Brillouin gain of the fiber medium. However, there is an intrinsic threshold for Brillouin oscillation even if the fiber is lossless because sufficient feedback must be built up for the oscillation condition to be satisfied[1]. Further addition of linear loss simply means more pumping will be required to achieve the same amount of feedback, thus a higher threshold.

We have predicted in the backward scattering case a drastic reduction in the laser pump throughput at approximately three times the initial pump threshold for the onset of backward scattering[1]. With predicted threshold powers for present fibers in the range of 35 mW in the case of stimulated Brillouin scattering we can readily achieve powers manyfolds above threshold so that verification of the entire range of transmission characteristics with varying incident pump power is possible. We have chosen to study the Brillouin

process fully since its threshold is approximately two orders lower than that for the Raman process. We will attempt to study the latter if laser power is available and damage has not set in resulting from the Brillouin process.

REVIEW OF CURRENT RESEARCH IN FIBER TRANSMISSION ACCOMPANIED BY STIMULATED SCATTERING

Hill et al[3] have carried out experiments on a Brillouin laser using fibers pumped by an argon laser at 5145 Å, where fiber loss is less than 100 db/km, a core diameter of 2.4 μm and length 9.5 m. We can derive from their data the transmission coefficient at various incident pump levels. Saturation of the laser throughput is reported beyond a certain threshold. When incident pump value is below threshold the pump throughput gives the amount of power coupled into the fiber so that its value serves as the incident pump value. This coupling is constant so that it can be extrapolated to any incident power levels. The transmission coefficient, which is the ratio of pump throughputs with and without stimulated scattering, is thus unity below threshold and decreases above threshold. Knowing the threshold incident pump value we can normalize other values giving the threshold a value of $\pi/2$. The experimental points can then be plotted and compared with our theoretical curves (see Fig. 1). The points appear to lie consistently above our computed curves.

Before any conclusion is drawn on the result, a few distinctive features of Hill's experiment must be pointed out that may have led to the discrepancy. Firstly, some external feedback was introduced in the form of a 4% mirror so that in our terms we are dealing with a case of Brillouin amplification, which has a lower threshold ($\sim$ 250 mW) according to our theory.[4] This is evident in Hill's work when we can see the beginning of another threshold at much higher incident pump values when this feedback is removed. In our work on bulk materials we observed the closeness of the Brillouin and damage thresholds. Hill did not report damage although he has gone substantially above the

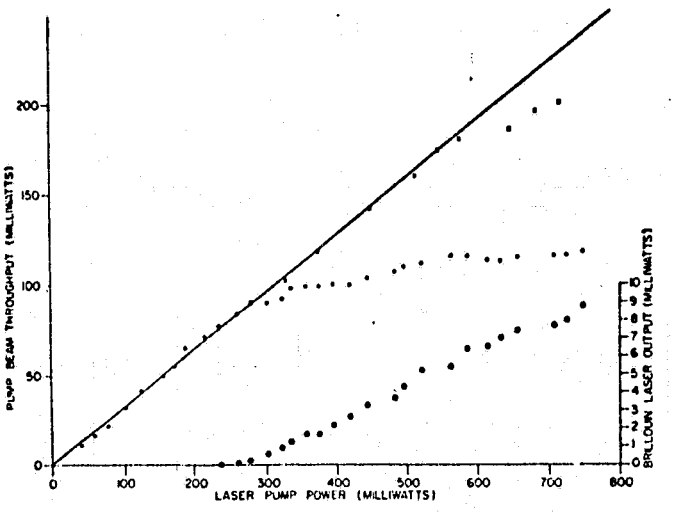

FIG. 1. Graph showing the variation with laser pump power of (1) throughput pump with feedback path broken between 4% and 50% reflectors (×); (2) throughput pump with feedback path intact (●); (3) Brillouin-shifted output power through 50% partial reflector (○).

Taken from Ref. 3

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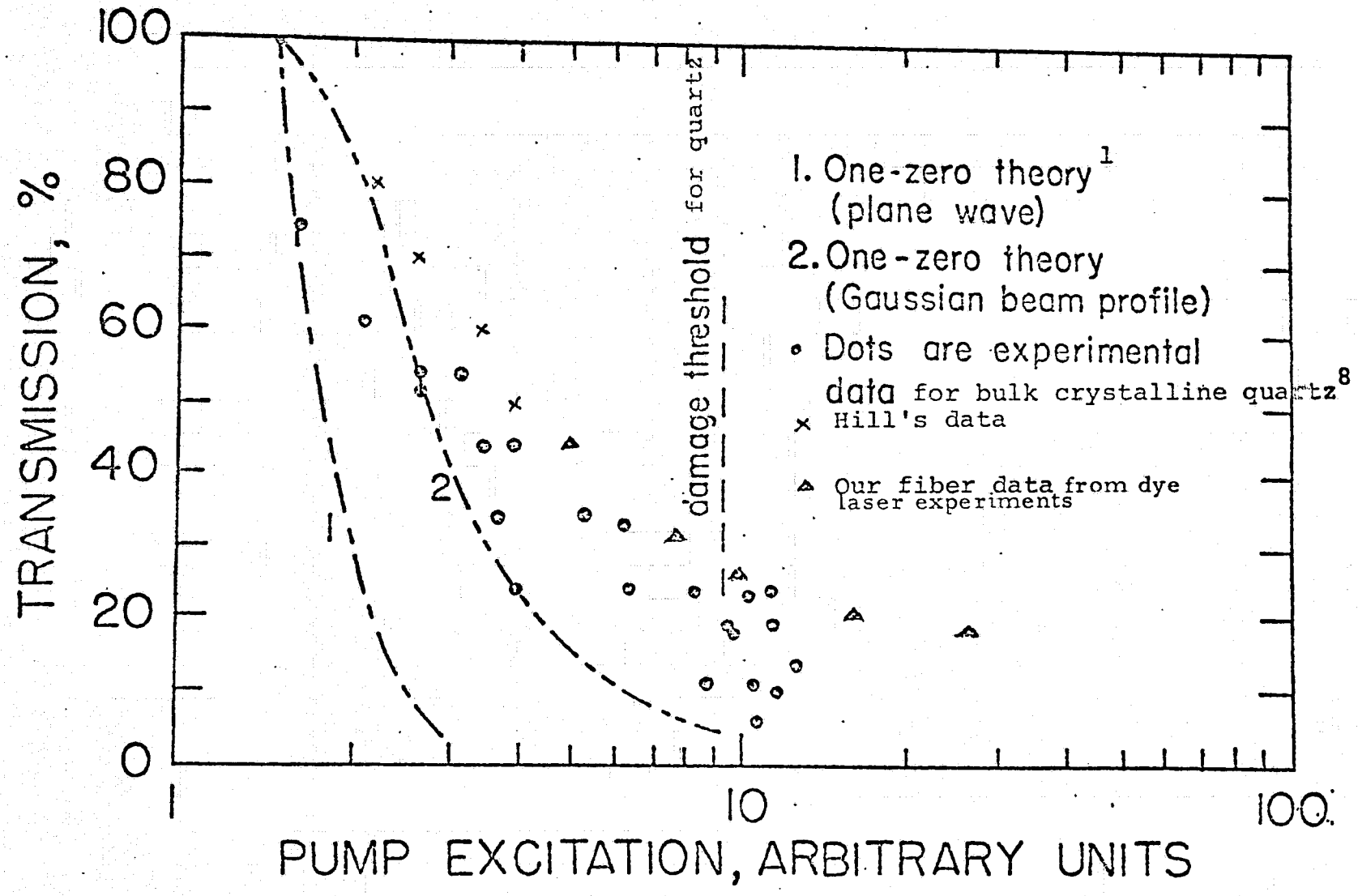
100
80
60
40
20
0
TRANSMISSION, %
1
10
100
PUMP EXCITATION, ARBITRARY UNITS
damage threshold for quartz
2
1. One-zero theory [1]
(plane wave)
2. One-zero theory
(Gaussian beam profile)
Dots are experimental data for bulk crystalline quartz [8]
Hill's data
Our fiber data from dye laser experiments

Fig. 2

Brillouin threshold. On the other hand, in Ippen's work[5], where there was no external feedback, damage was observed after the onset of Brillouin oscillation. No quantitative data were given in the latter paper except a critical pump power of a watt. Taking into account the difference in core diameter, Ippen's threshold is still at least twice that of Hill's.

If Hill's work is indeed Brillouin amplification, then I would have used an incorrect threshold value of $\pi/2$ for normalization. I have computed various amplification curves at different gain values and Hill's experimental data may very well fit one of those curves.

Our task is thus to clarify the data reported by these two groups using our theory and carrying out a series of experiments.

Hill et al[6] have also reported the observation of simultaneous oscillation of a number of Brillouin Stokes and anti-Stokes lines in a scheme of the so-called cascade stimulated Brillouin scattering. Since no quantitative data are given, we cannot correlate it with the theory we have established for multiple wave interactions[7]. We are therefore very much interested in covering the entire range of incident pump powers so as to try to obtain these lines and the quantitative data on the laser throughput.

Another possible cause of the discrepancy between Hill's data and our computed curves involves linear loss in the fiber. Although the fiber is considered low-loss, it may be significant enough to bring about a shift in the no-loss threshold established in our theory. Such a shift is always towards higher pump values as to be expected since a higher pump is now required to overcome loss besides building sufficient feedback gain. We will thus qualitatively anticipate a shift of the experimental curve to the right as evidenced in Hill's data.

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PRESENT STATUS OF OUR WORK

We have operational, a tunable dye laser with internal etalon as the pump source capable of giving out 30 nsec pulses of KW power with pulse repetition rate ranging from 5 per sec to 200 per sec. We have acquired an assortment of detectors, microtranslation stage, microscope objective, laser power meter, standard optical components, and a fast scope. Most of these items are mounted on an optical table with vibration isolation. The most difficult item to obtain is the single-mode fiber. Apparently, it is not yet commercially available. It was virtually by accident that we came across one supplier who could provide 10 m of 2.5 μm core fibers, and a similar fiber was given by Bell Labs.

Coupling of laser light into such a small core fiber is quite a tricky affair and involves some rather delicate maneuvers. The fiber is attached to the microtranslation stage for fine xy movements and laser light is focused into the fiber using the microscope objective.

Following Hill's technique total incident laser power and that focused into the fiber will be monitored simultaneously so as to establish their one-to-one relationship at low incident powers. A graph similar to Hill's thus establishes the coupling constant of such a system so that it remains the same at all incident power levels. As the incident power is raised, there will be the onset of the Brillouin scattering process, leading to depletion of the pump. The transmission coefficient as established previously will be determined. No external feedback path will be introduced in the oscillation case.

Some attempts will be made to carry out amplification experiments, although we are aware of the complications such as the necessity of knowing the gain of

the fiber system. However, data obtained may have important consequences since this mechanism may amplify signals in the fiber when used as optical communication channels.

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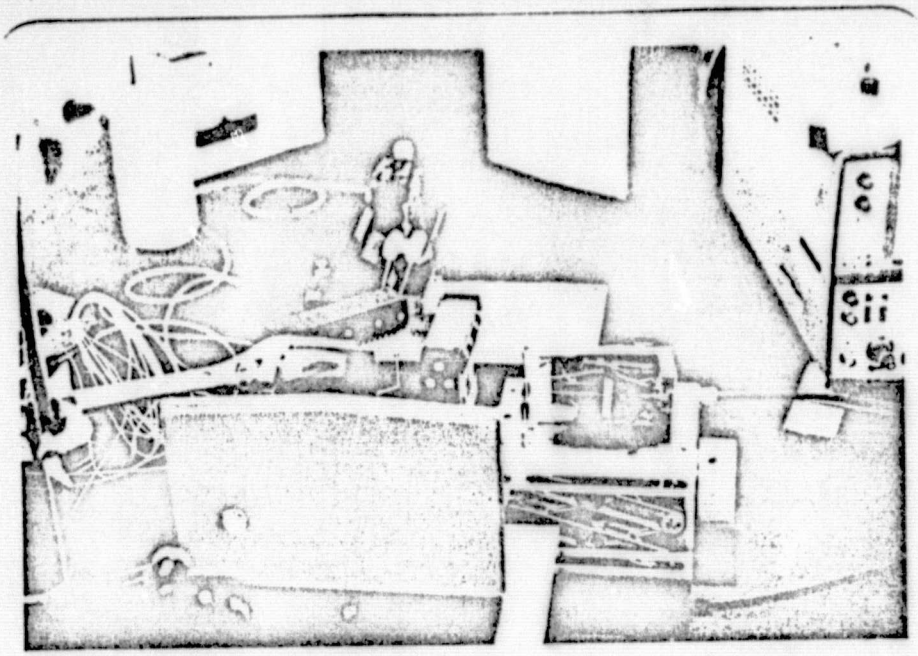

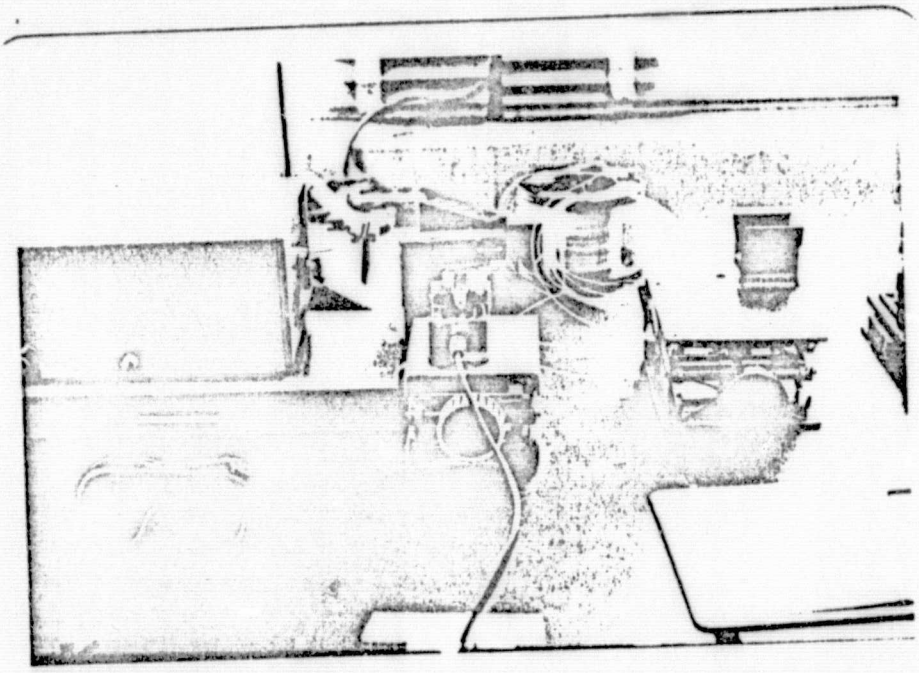

Fig. 3

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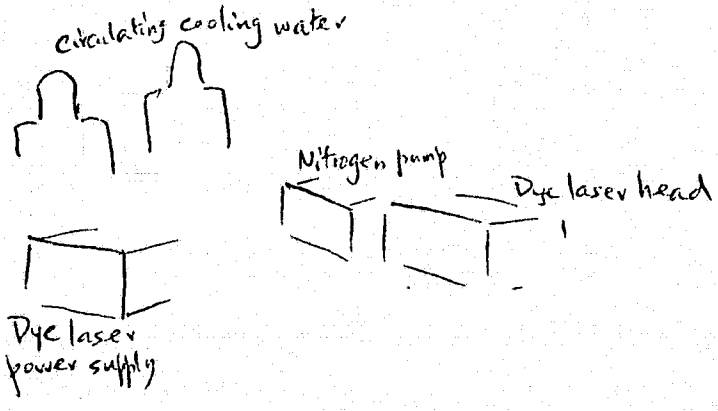

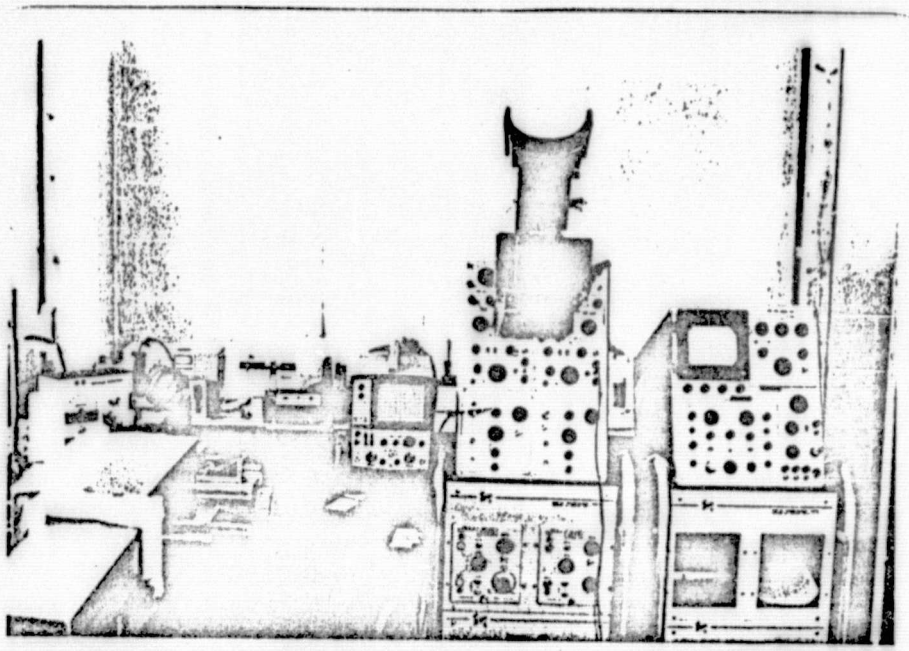

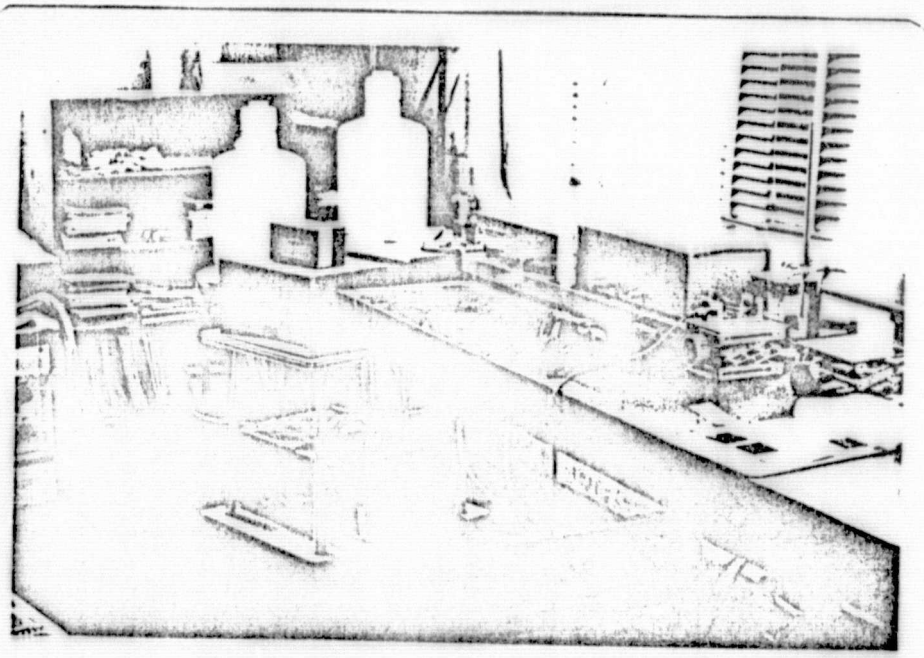

Fig. 3, cont'd

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RESULTS

A Laser Energy tunable dye laser is used as our laser pump giving 8 nsec pulses of 10^5 watt power. For higher power the laser is pulsed at 3 pulses per sec, and the power decreases with increasing pulse rate. The horizontal laser beam is deflected by a right-angle prism into a 20 X microscope objective for coupling into the 4 μm core fiber. The fiber ends have been carefully cleaved and examined under a microscope. The fiber is then mounted on an x-y axes microtranslation stage for easy and precision maneuvering of the fiber into the focus of the objective. This coupling of laser light into the fiber is optimized first visually by observing light transmission at the output end of the fiber and then refined by monitoring the photodiode output which is used to detect the light.

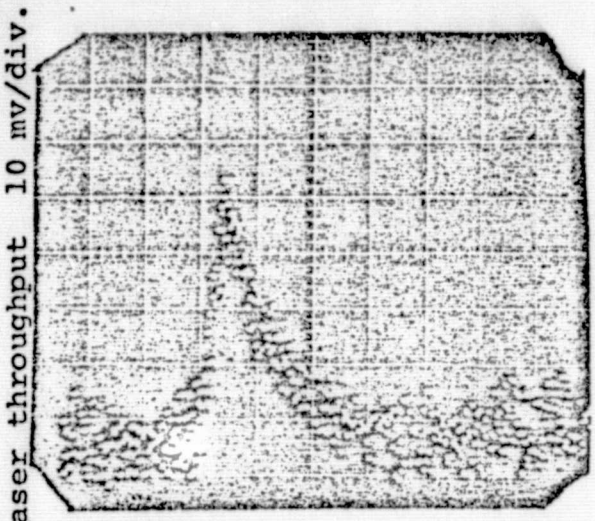
When the system is optimized, filters are introduced between the laser source and the prism as a means of varying the laser power incident on the fiber. The laser throughput at different incident power levels is recorded together with the incident power (see Fig. 4) on a sampling scope and photographed.

These two sets of power readings are then plotted following Hill's method. A threshold for the onset of saturation of the laser throughput is evident. The linear part of the curve is extrapolated to establish the actual incident power coupled into the fiber without stimulated scattering. A smooth curve is drawn through the experimental throughput points (Fig. 4 a) The ratio of the two curves gives us the transmission coefficient of the fiber.

This transmission coefficient is then plotted with the corresponding points on the extrapolated curve as values of the pump normalized to the

threshold value in Fig. 1. The points again lie to the right of the theoretical universal curve 2.

Our preliminary results seem to coincide with Hill's data, thus indicating the fact that Hill and coworkers were dealing with a much lower threshold since external feedback had been introduced.



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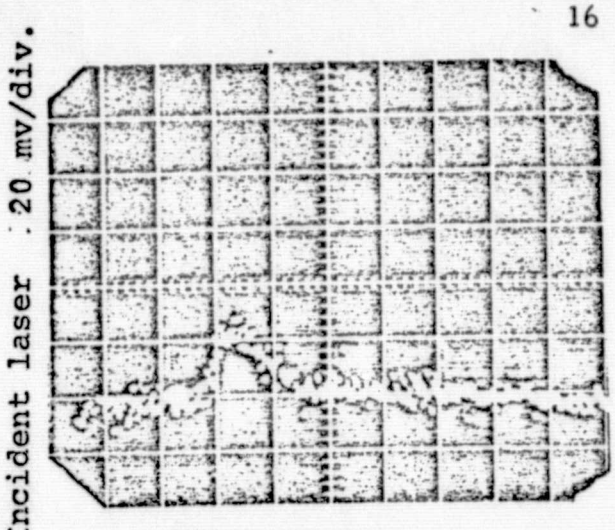

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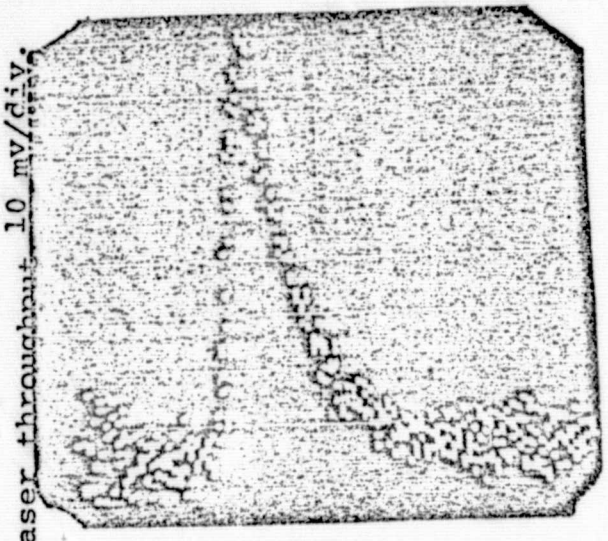

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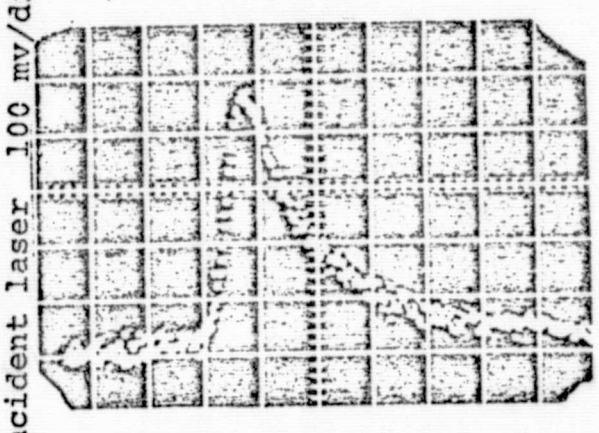

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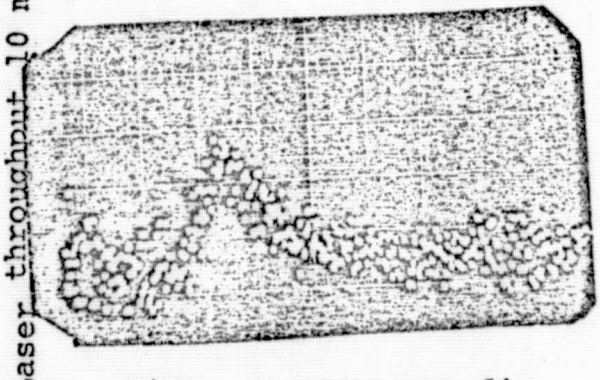

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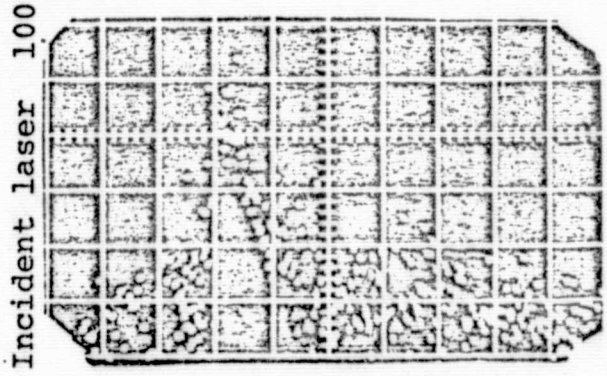

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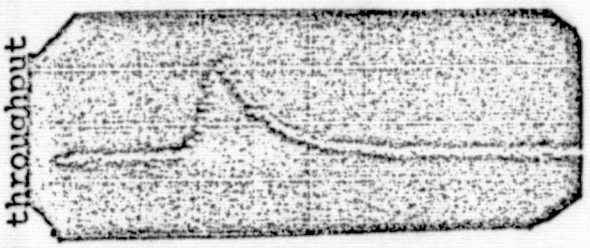
Fig. 4



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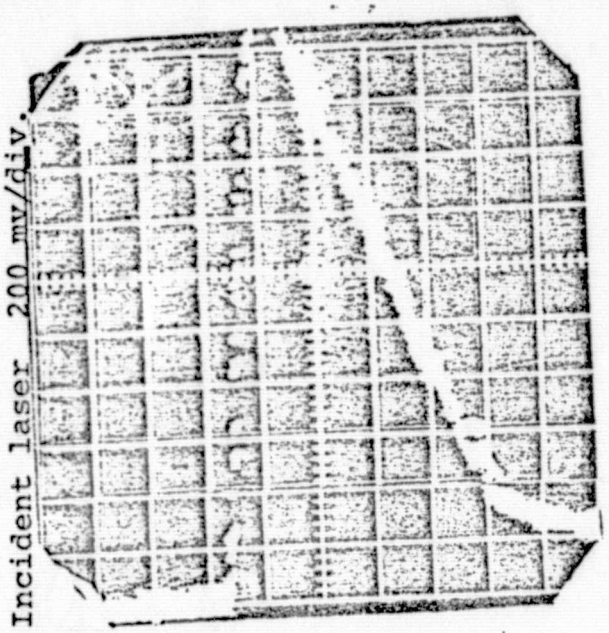

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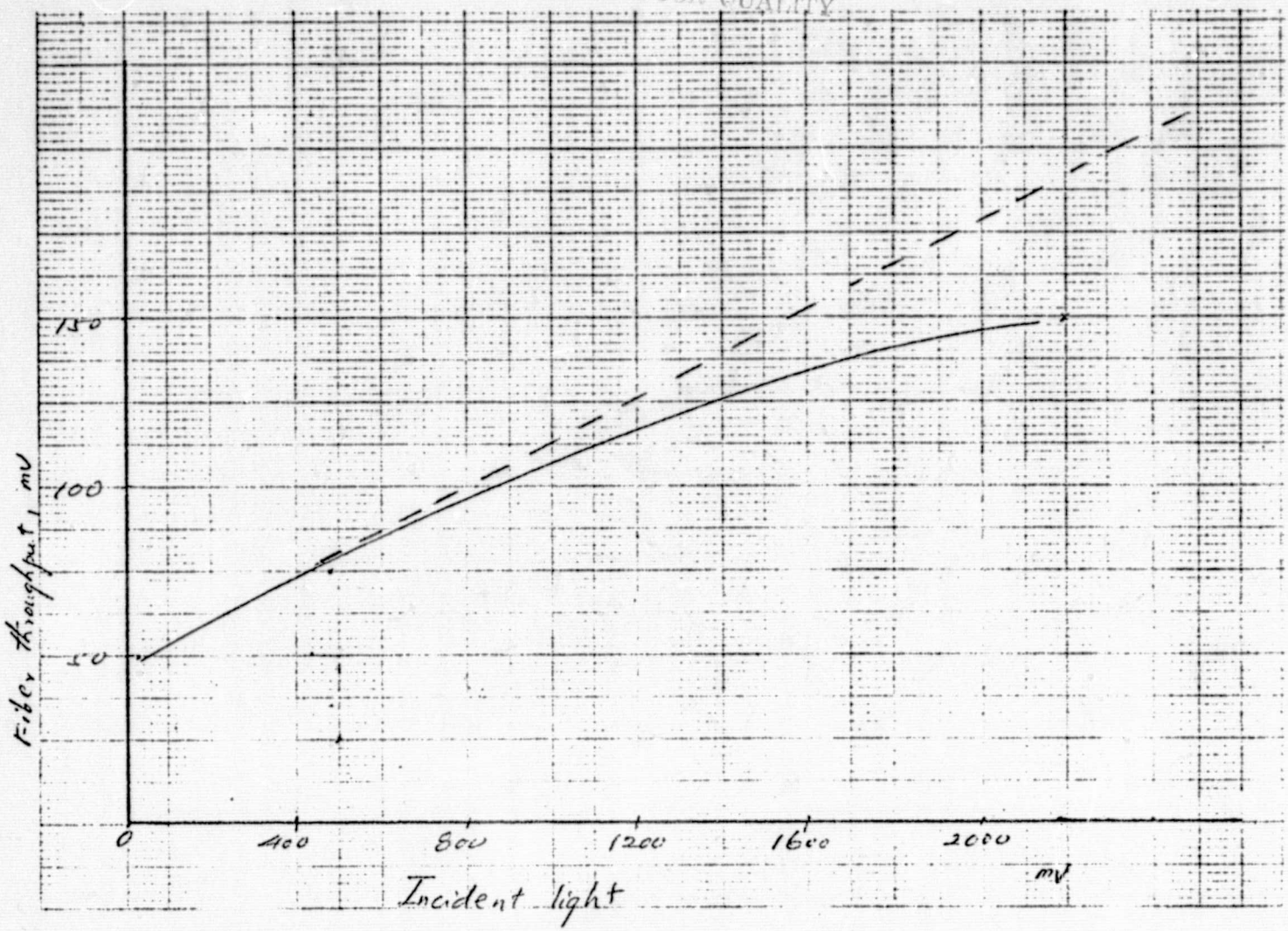


Fig. 4 a

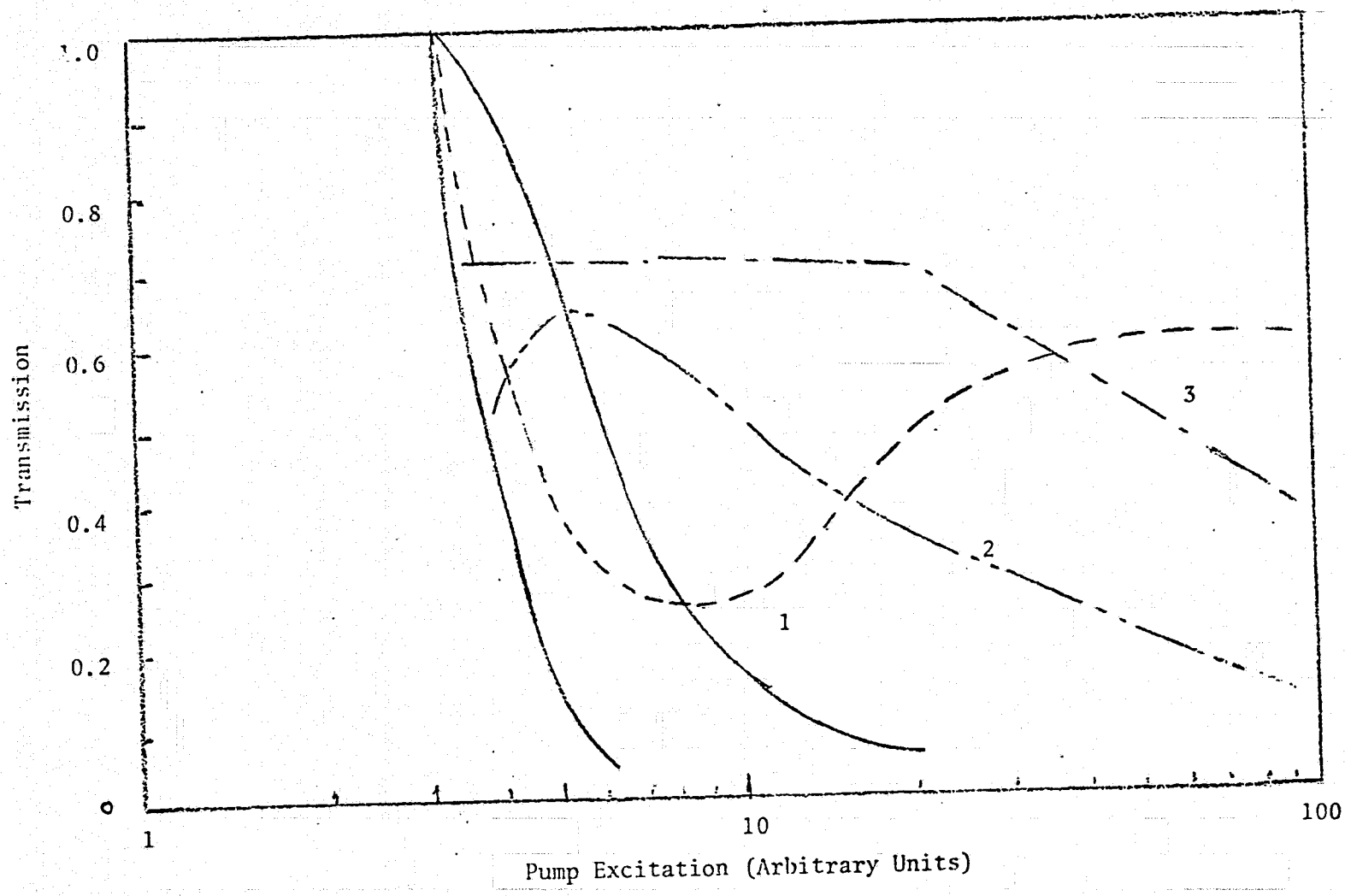

1.0
0.8
0.6
0.4
0.2
0
Transmission
1
10
100
Pump Excitation (Arbitrary Units)
1
2
3

Fig. 5

DISCUSSION OF DYE LASER RESULTS

Curve 1 of Fig. 5 indicates a drastic drop in transmission with increasing incident laser power into the fiber. It seems to approximate the transmission curve computed with the one-zero plane wave theory. However, transmission improves again at higher incident laser power laser power levels contrary to the continue drop predicted by theory. This may be attributable to damage in the fiber resulting in increased normal scattering of stimulated backward scattered light forward, hence seemingly higher transmission for the incident laser.

We were not able to verify this series of data. Curves 2 and 3 were usually obtained instead. Most recent data indicated even flatter curves showing the disappearance of stimulated scattering processes.

The critical aspect of our results may in part be due to the broad linewidth of the laser pump. We were able to narrow the width only to 0.1 nm, while theory called for a width of 100 MHz. As a consequence, the threshold for the onset of stimulated Brillouin scattering was raised considerably. Higher incident laser power was thus required, which then caused damage in the fiber, as has been observed by Ippen, et al.

A rather broad linewidth was employed in our case since we predicted in our theory (see Appendix 1) it would be equivalent to miltiple wave pumping and this should help to lower the SBS threshold. It appears that a better means to realize multiple-wave pumping is to use multiple lasers of narrow linewidth.

Since we first proposed this work, Raman and Brillouin lasers have been realized with tunability. There is definitely a trend towards using fibers as nonlinear optical devices so that basic understanding of the nonlinear scattering mechanism is important.

EXPERIMENTS USING ARGON LASERS

A similar series of transmission experiments was conducted using a TRW 71B argon laser with a narrower linewidth of a few GHz. Although the laser has a multi-line single-mode power of 0.8 W per pulse, the single-line power at 5145 Å is only 0.1 W. Transmission was found to be linear.

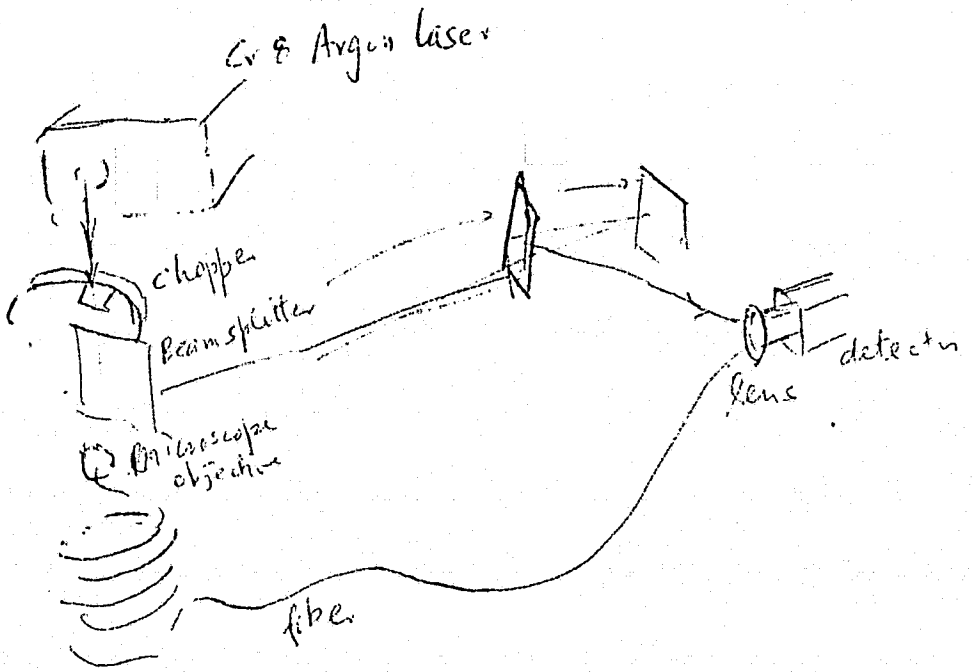
We then proceeded to a higher-power laser, in this case, a Coherent Radiation Cr 8 argon laser with multi-line capability and a 5145 Å line power of 1.6 W cw. The power is varied by varying the discharge current and light output is automatically stabilized. The cw laser beam could be mechanically chopped and detected. The experimental setup was photographed and schematically shown.

In the standard setup the pump beam was focused into the tip of the fiber by a microscope objective. When two lasers were used simultaneously, the TRW laser beam was steered by an off-axis parabolic mirror to the microscope objective so that both this beam and the pump beam could be kept parallel for maximum coupling into the fiber in the forward-traveling-wave configuration. To establish a backward-traveling-wave configuration, the TRW laser beam was focused by a lens into the other end of the fiber so that after exit it would be approximately collimated by the microscope objective. This emerging beam could also be collected by the same off-axis parabolic mirror except that the detected signal would be quite severely masked by the pump light. The cw pump light was not detected but its intenseness tended to saturate the detector for the detection of the weaker signal.

Linearity of the detector response was extremely critical in studying the saturation or nonlinear effect in light transmission through a fiber. Great care was thus exercised to keep the detected signals from both lasers at approximately the same level. The following figures will show that slight saturation of the detector could completely alter our experimental data.

Since there were so many variations to our basic experimental setup, illustration of the experiment will be best served by attaching a simple schematic of the variation to each set of experimental results together with a brief description.

EXPERIMENTS USING ONE ARGON LASER



Laser Transmission experimental setup

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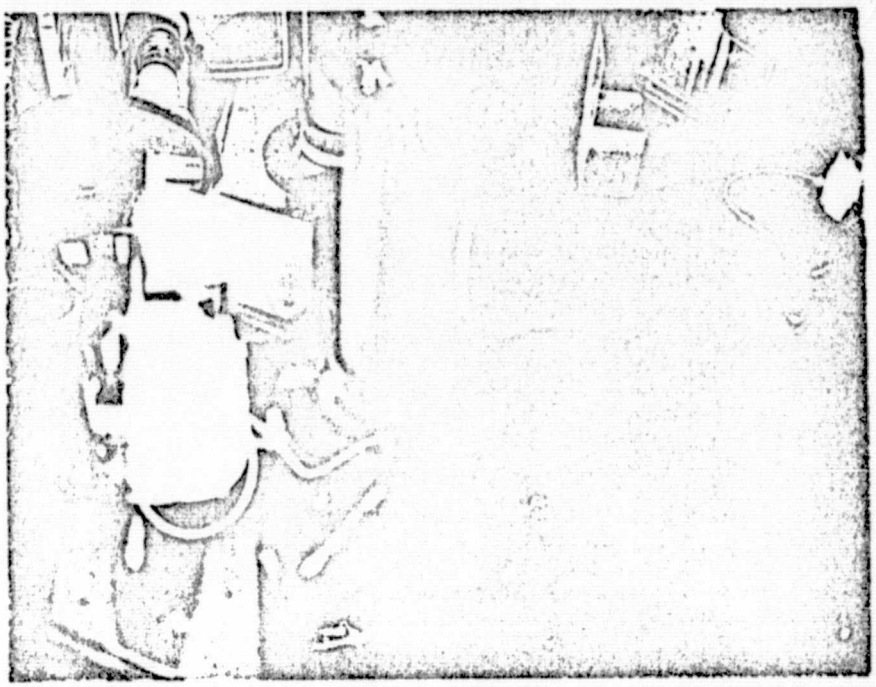
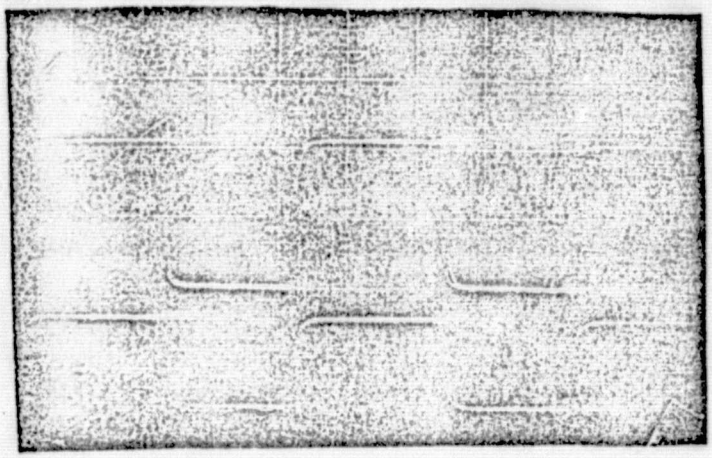


Fig. 6



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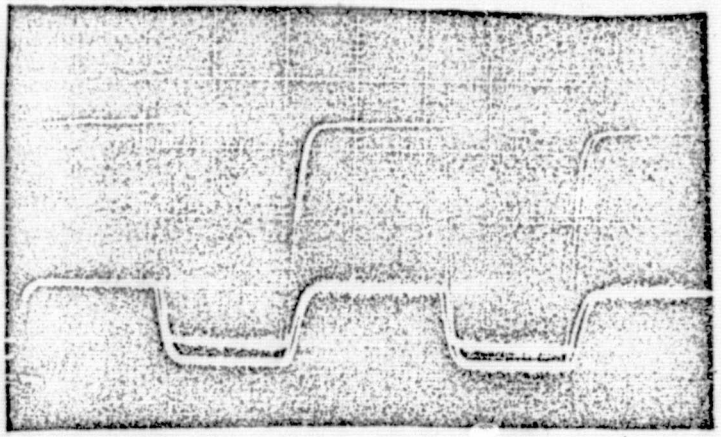

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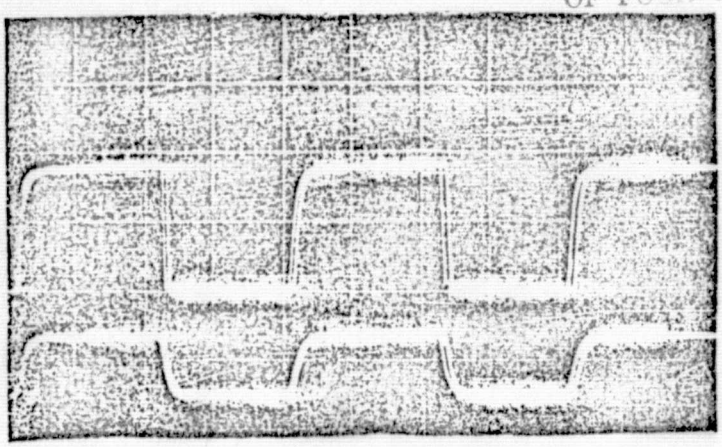
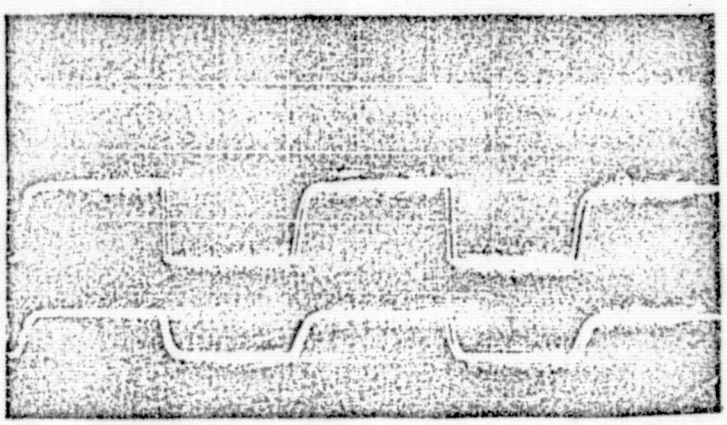
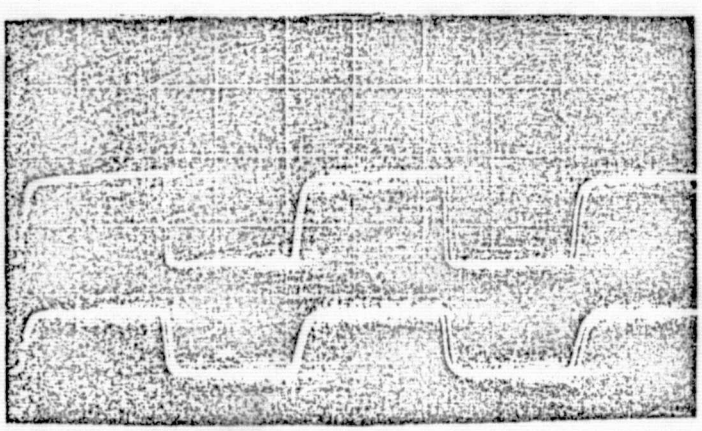


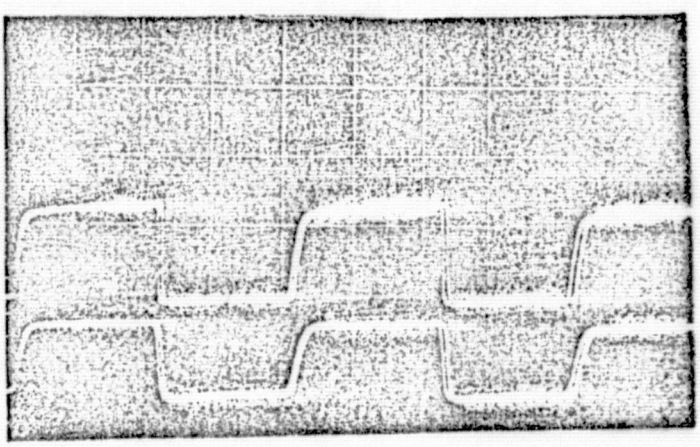
0.05 V/cm



0.1 V/cm



0.1 V/cm



0.1 V/cm

Top trace: fiber throughput , Bottom trace: incident pump

Fig. 7 . Detector output

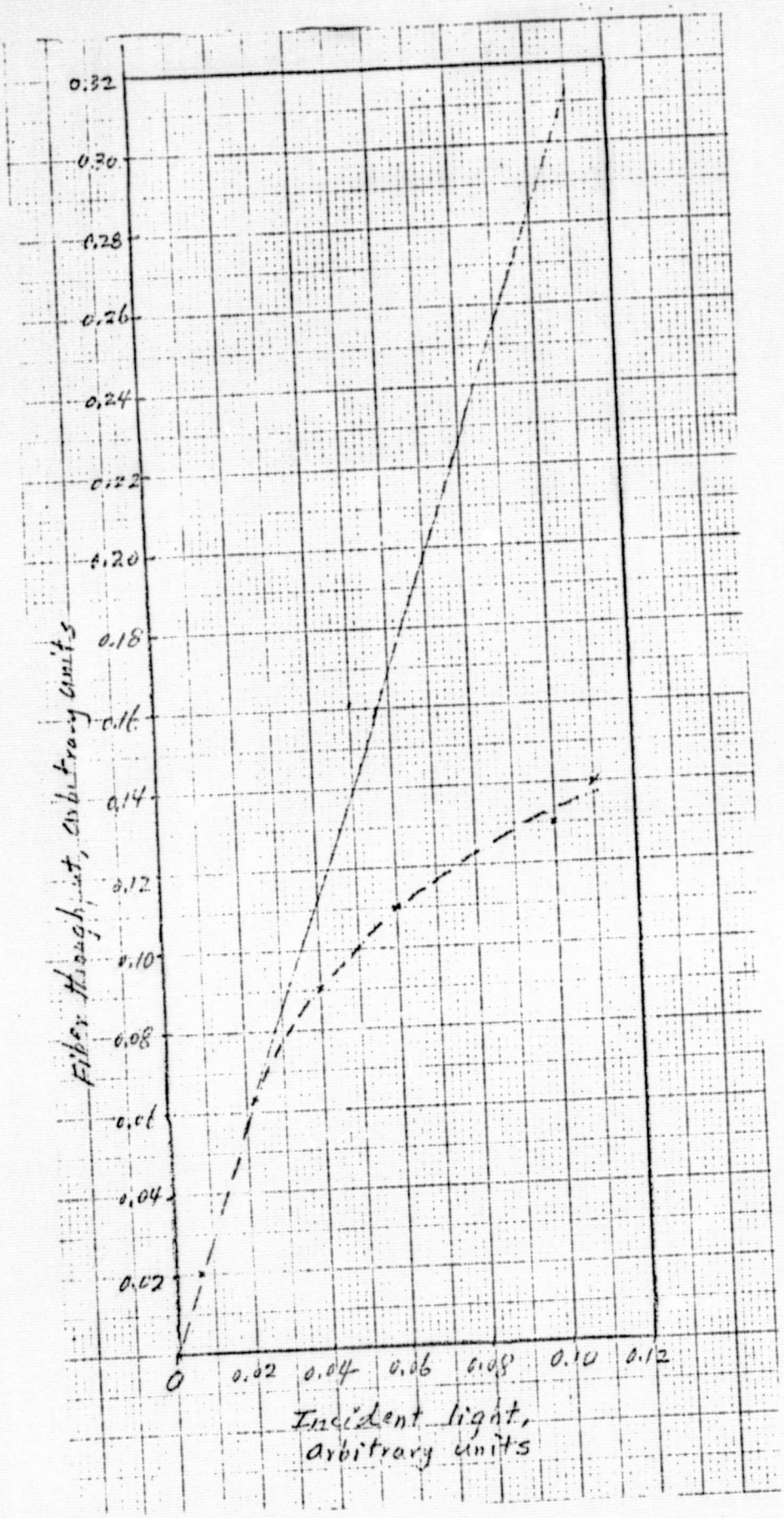
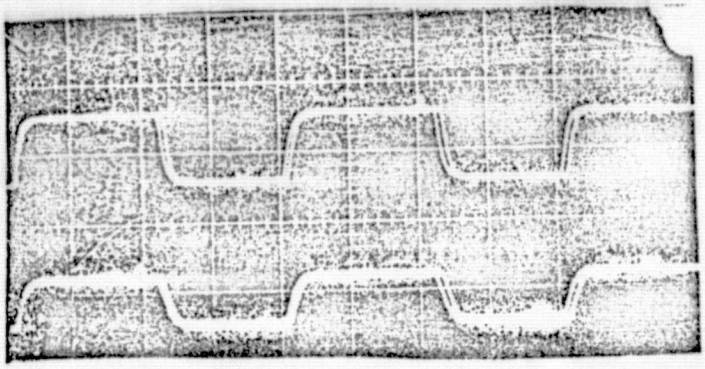
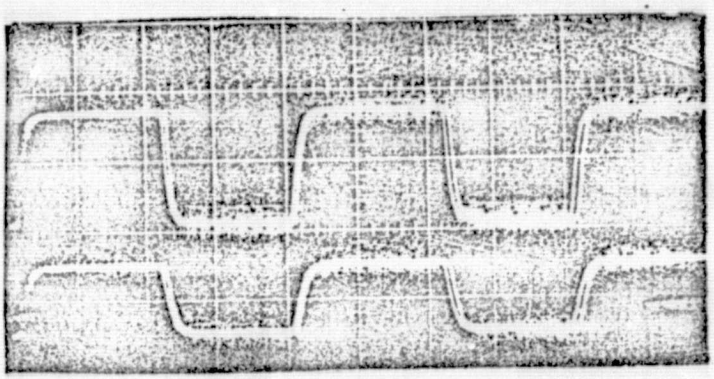

0.32
0.30
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
Fiber throughput, arbitrary units
0
0.02
0.04
0.06
0.08
0.10
0.12
Incident light, arbitrary units

Fig. 8



0.005 V/cm



0.01 V/cm

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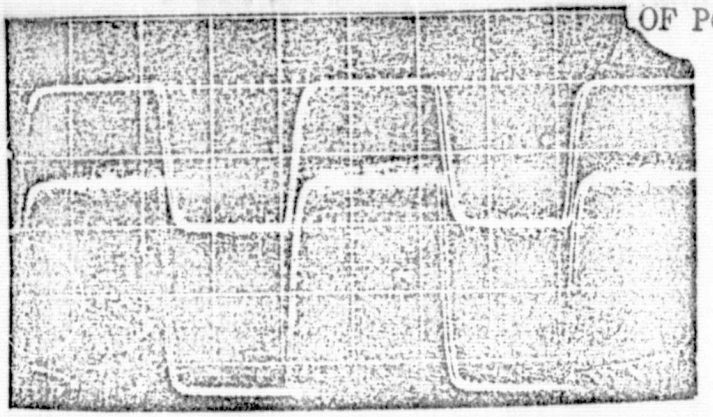
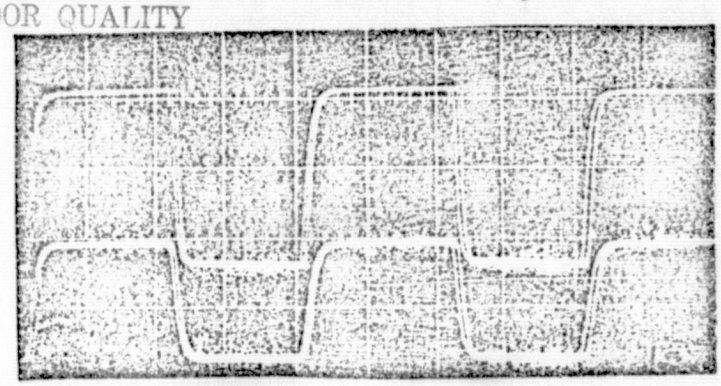
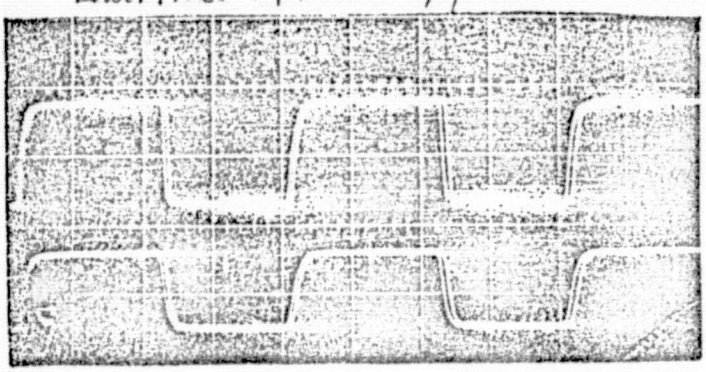


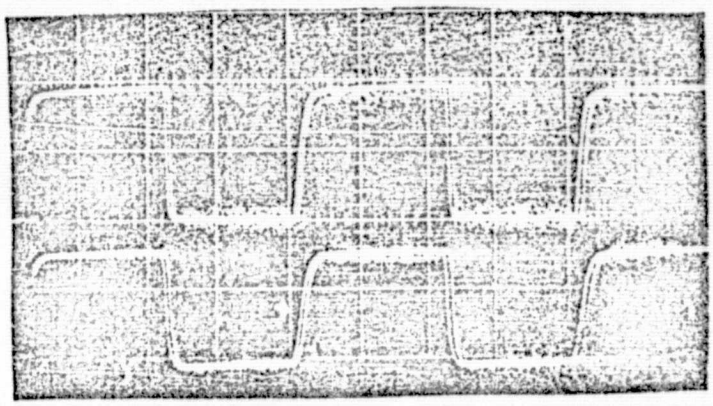
0.01 V/cm
Lower trace = fiber throughput



0.02 V/cm

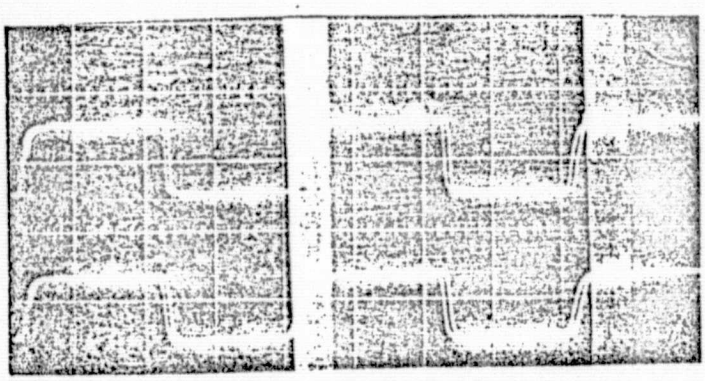


0.05 V/cm

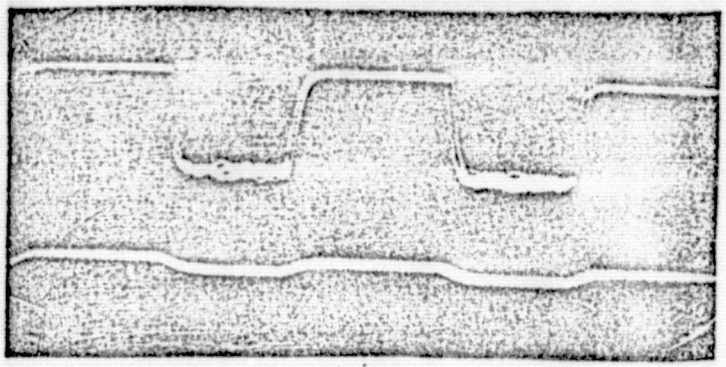


0.05 V/cm

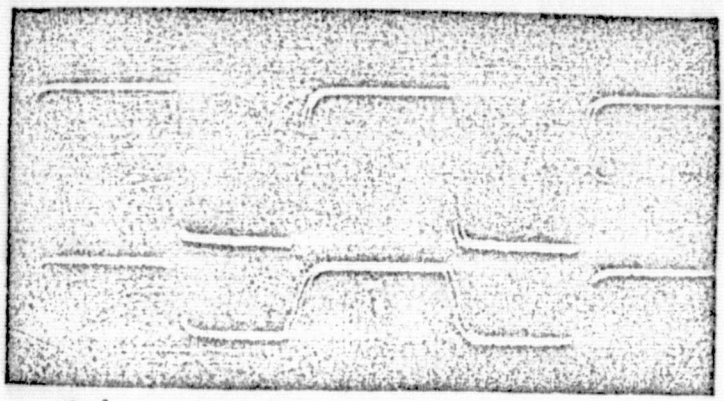
Fiber throughput followed incident "



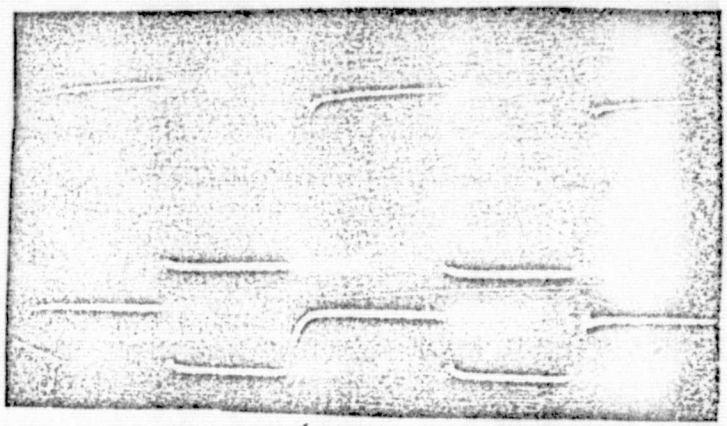
0.1 V/cm



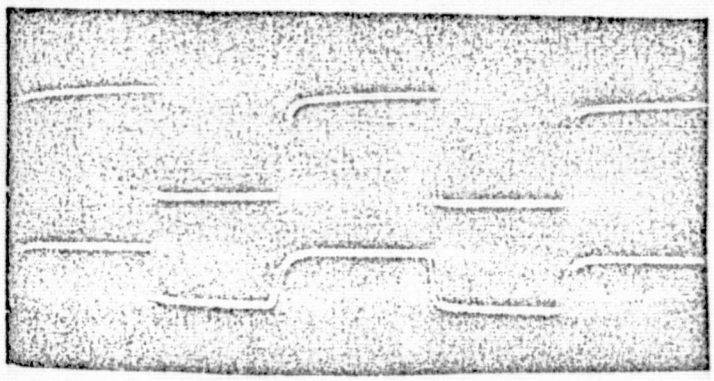
0.05 V/cm



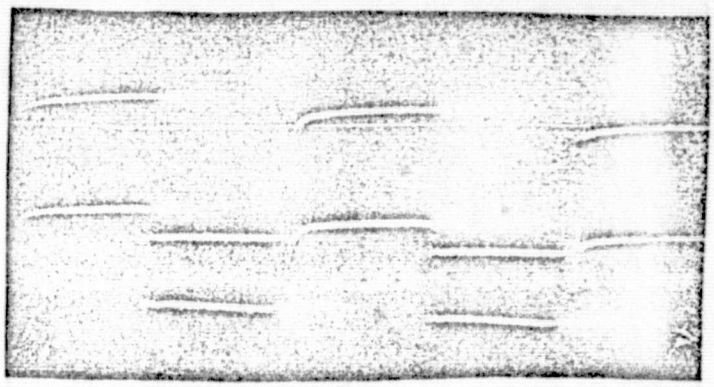
TOP: 0.02 V/cm
BOTTOM: 0.005 V/cm



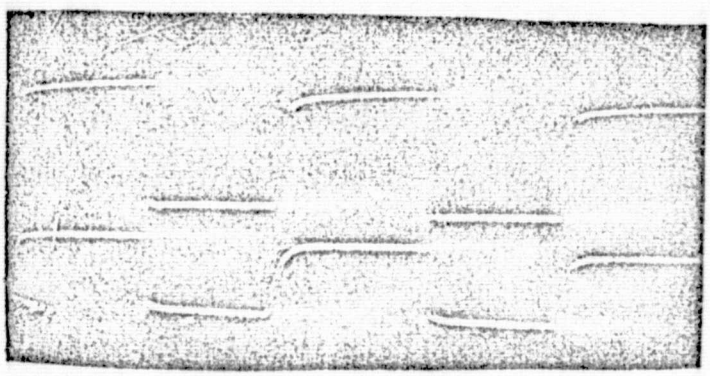
0.05 V/cm



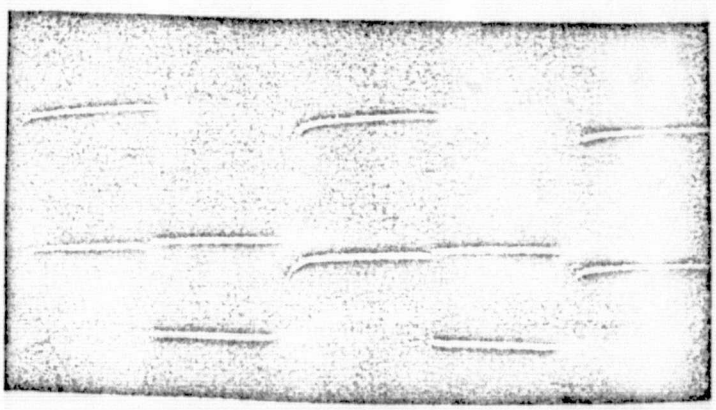
0.1 V/cm



0.1 V/cm



0.1 V/cm



0.1 V/cm

Fig. 10

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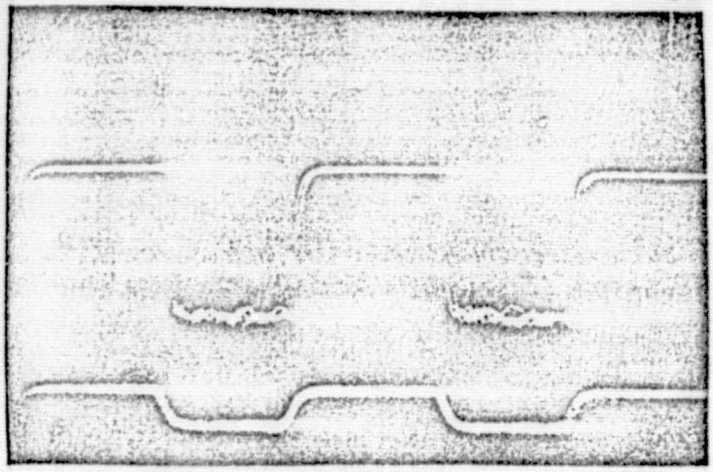
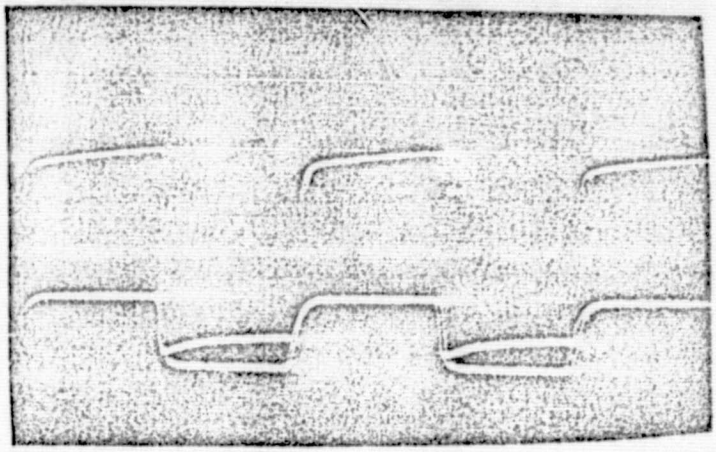
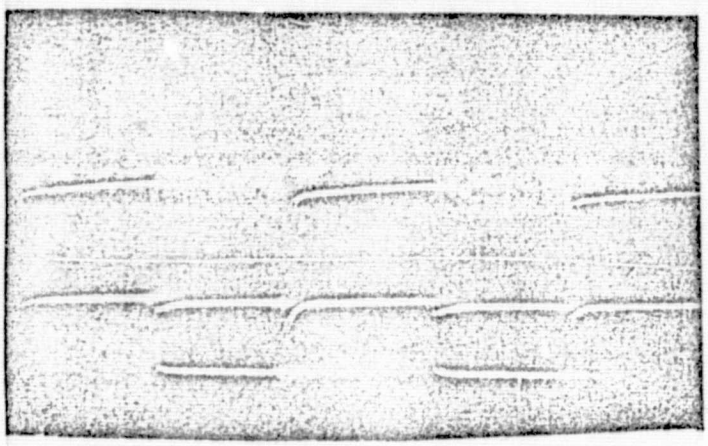


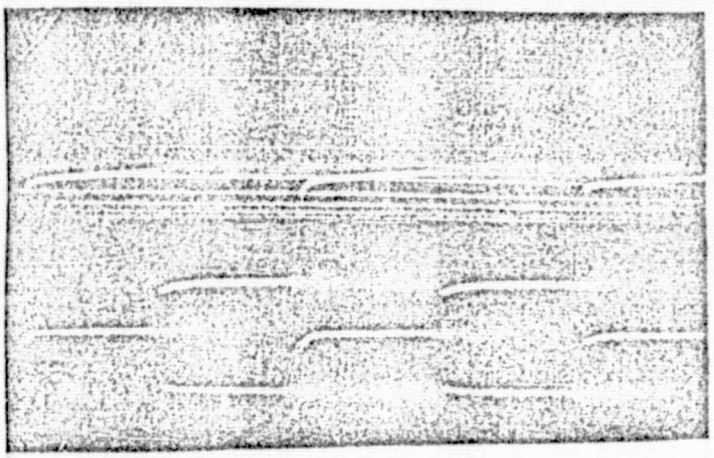
TOP : 0.02 V/cm
BOTTOM : 0.005 V/cm



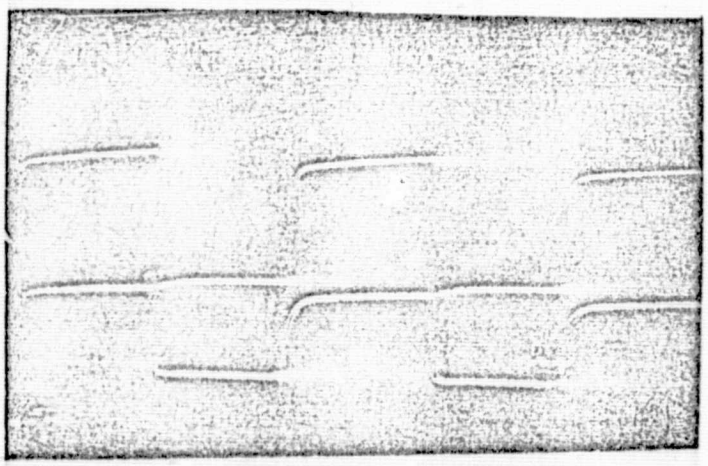
0.05 V/cm



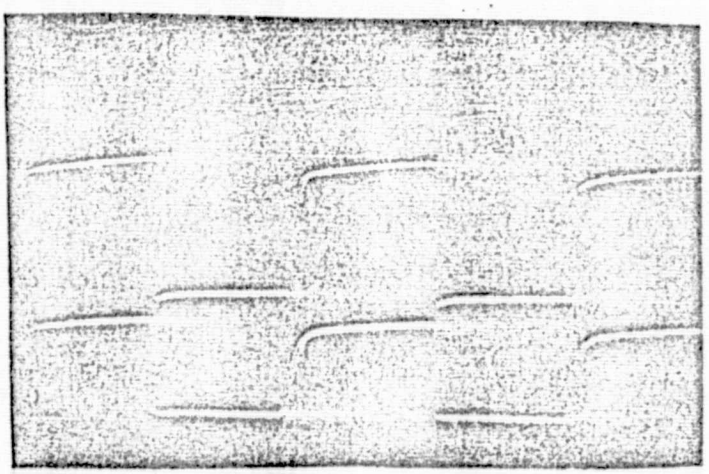
0.1 V/cm



0.1 V/cm

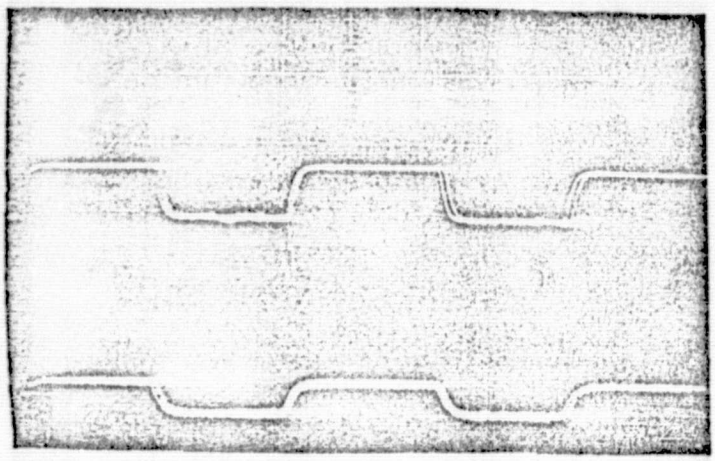


0.1 V/cm

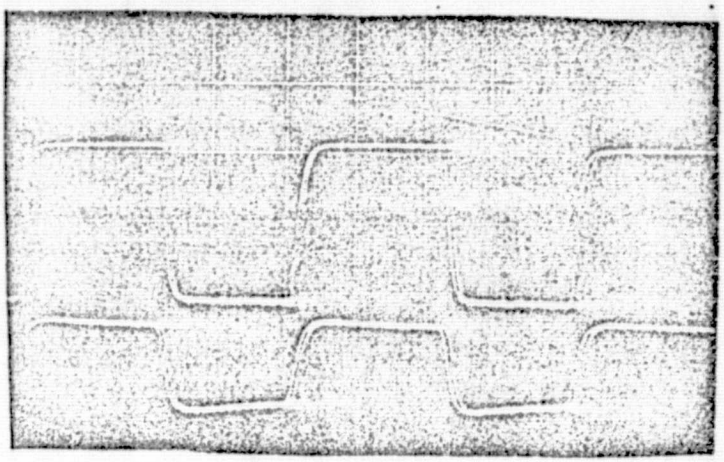


0.1 V/cm

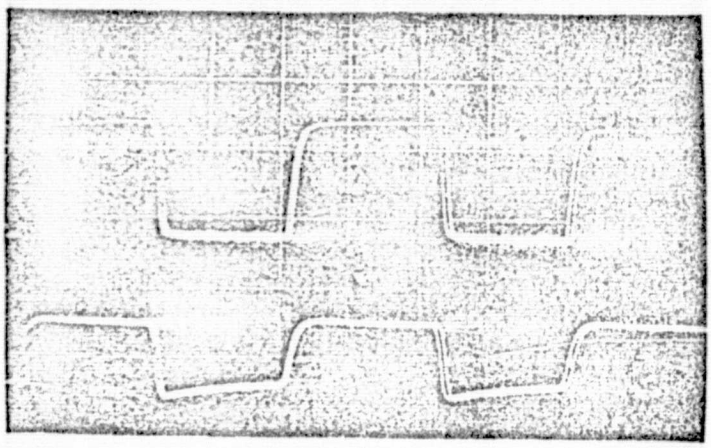
Fig. 11



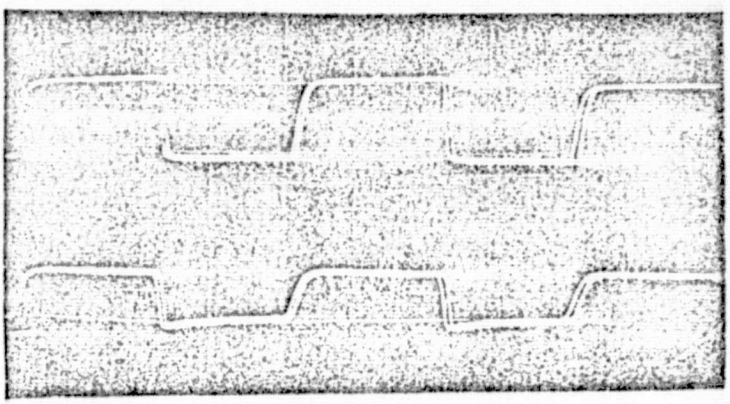
0.005V/cm



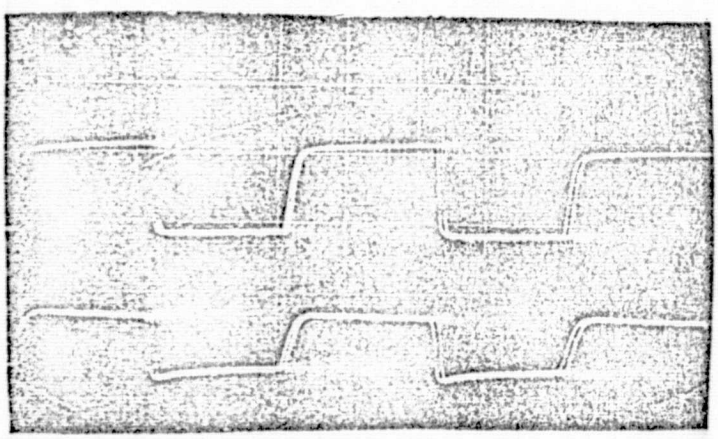
0.01 V/cm



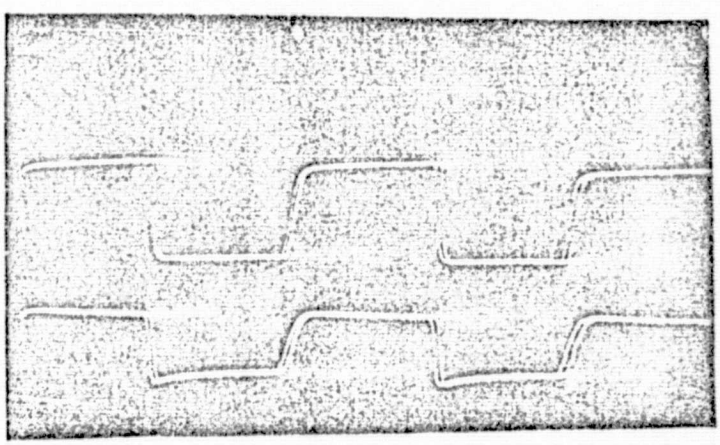
0.05V/cm



0.1V/cm



0.1 V/cm



0.1 V/cm

Fig. 12

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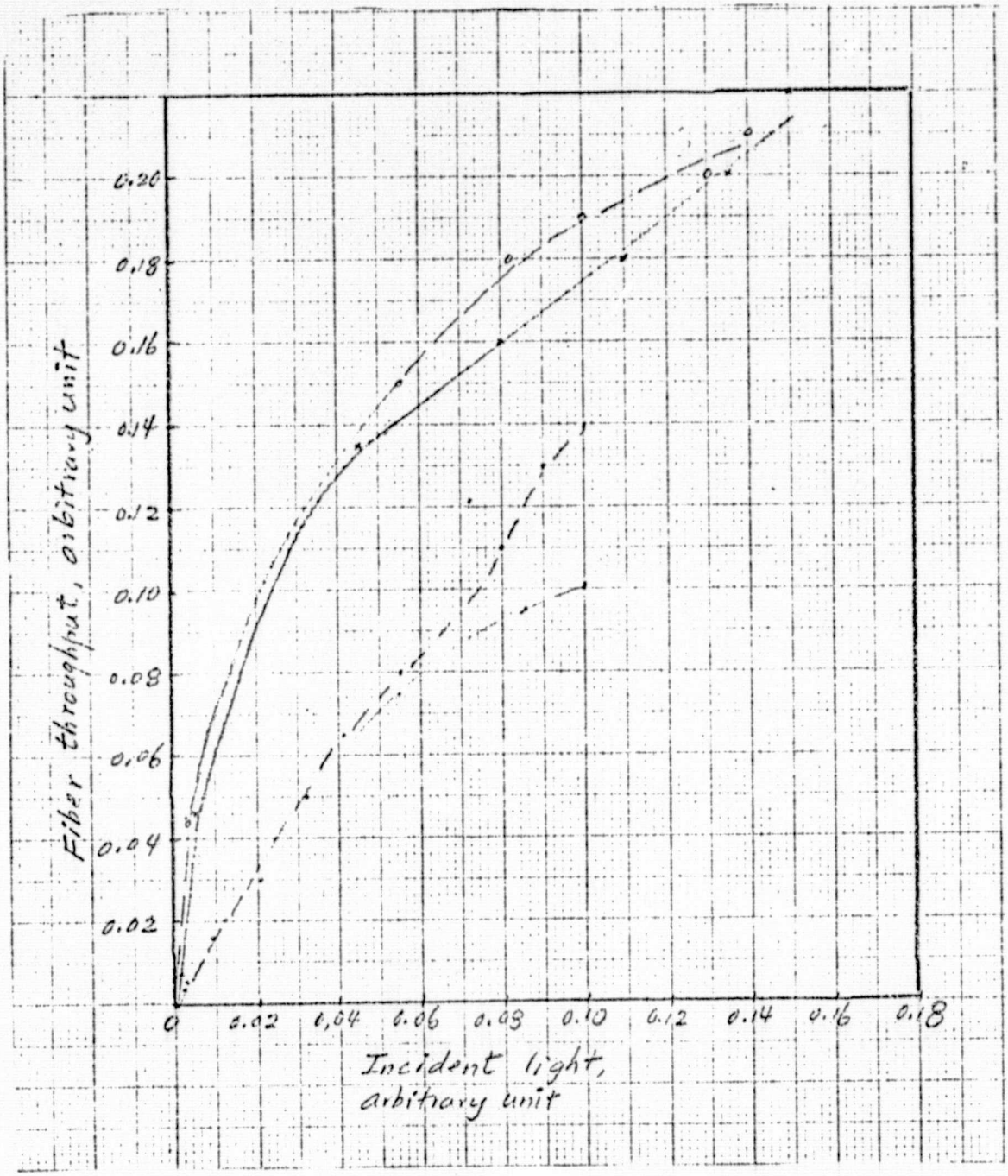

Fig. 13

EXPERIMENTS USING TWO ARGON LASERS (PART I)

The low-power TRW laser was directed as signal into the fiber together with the Cr 8 high-power laser pump as shown in Fig. 14. This is the forward-traveling-wave signal case.

The signal level is seen to decrease with increasing incident pump power (pump power ranges from 0 to 1.6 W in Figs. a - e). Such variation is plotted in Fig. 15. The detected signal pulse is shown at various pump power levels in Fig. 16.

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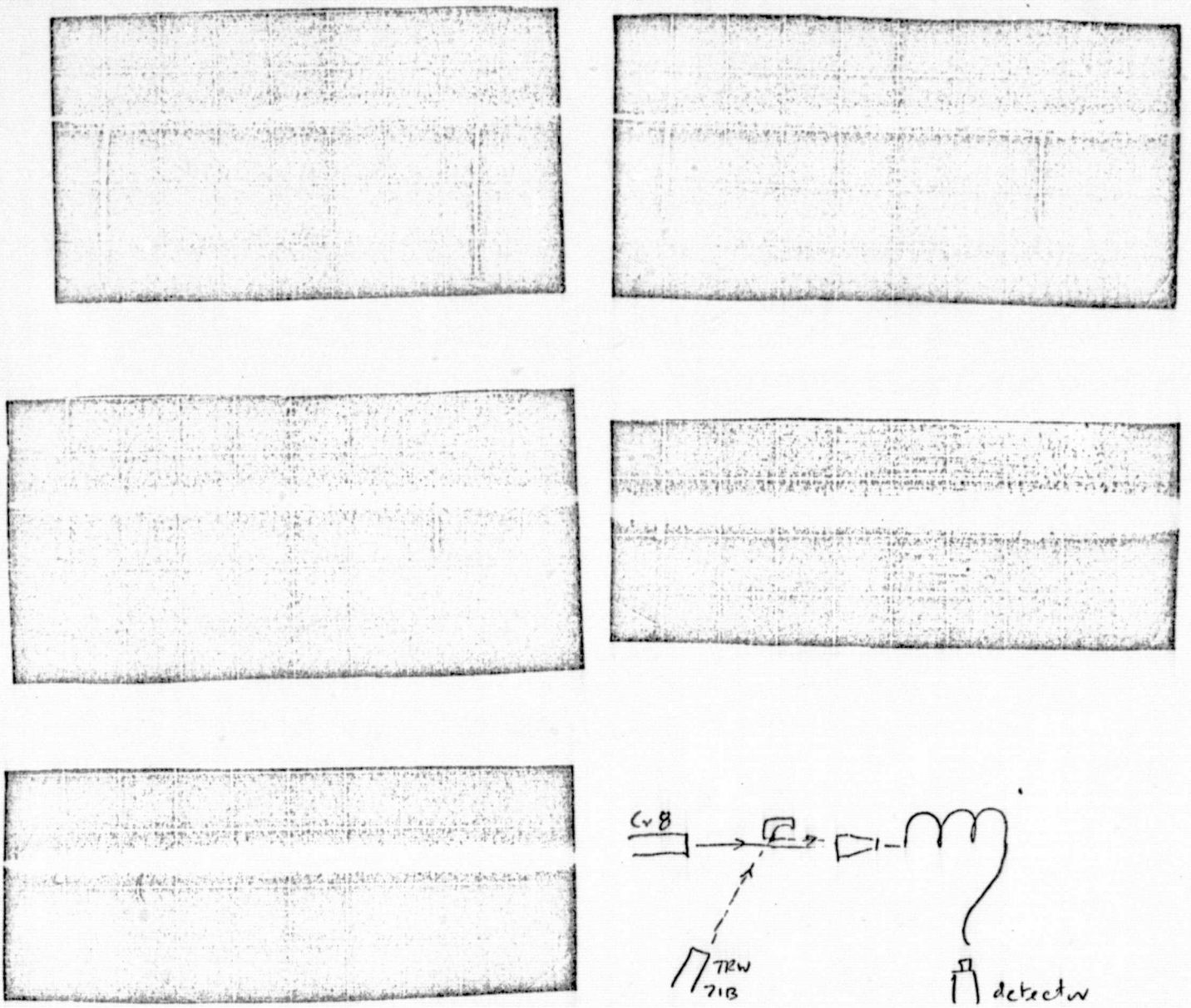

Fig. 14. TRW laser pulse at various Cr 8 laser pump levels

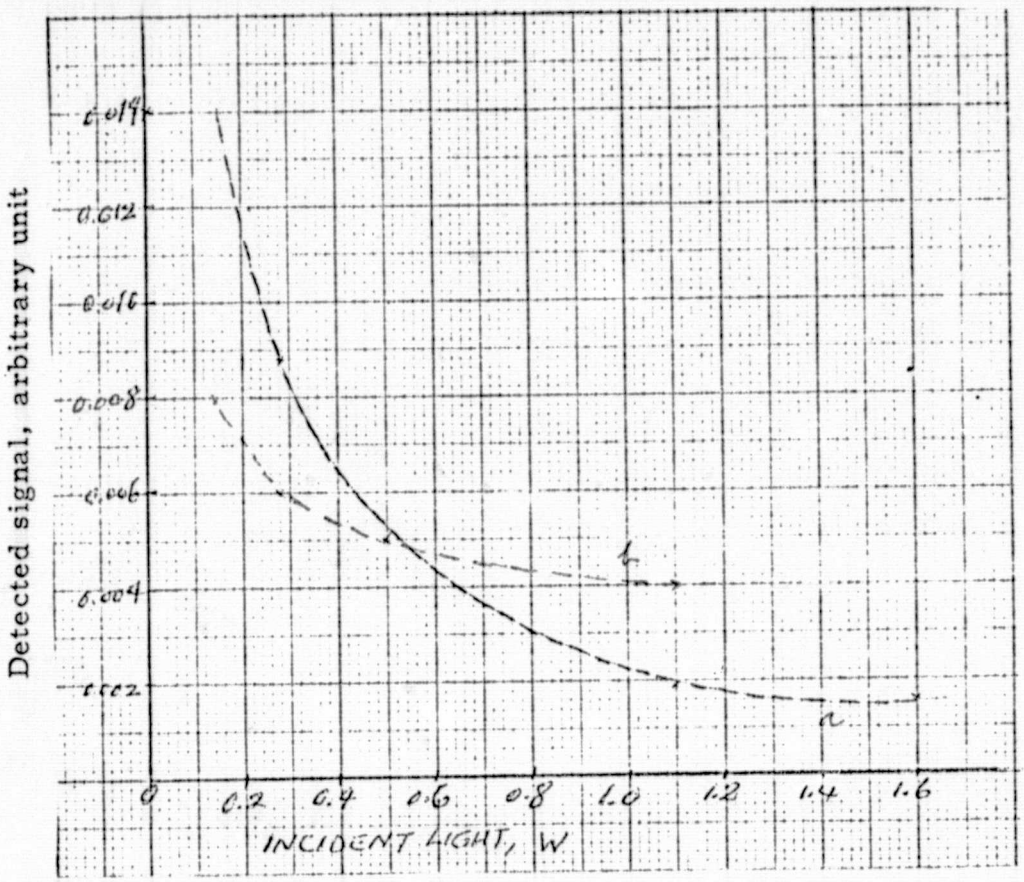

Fig. 15, FTW signal

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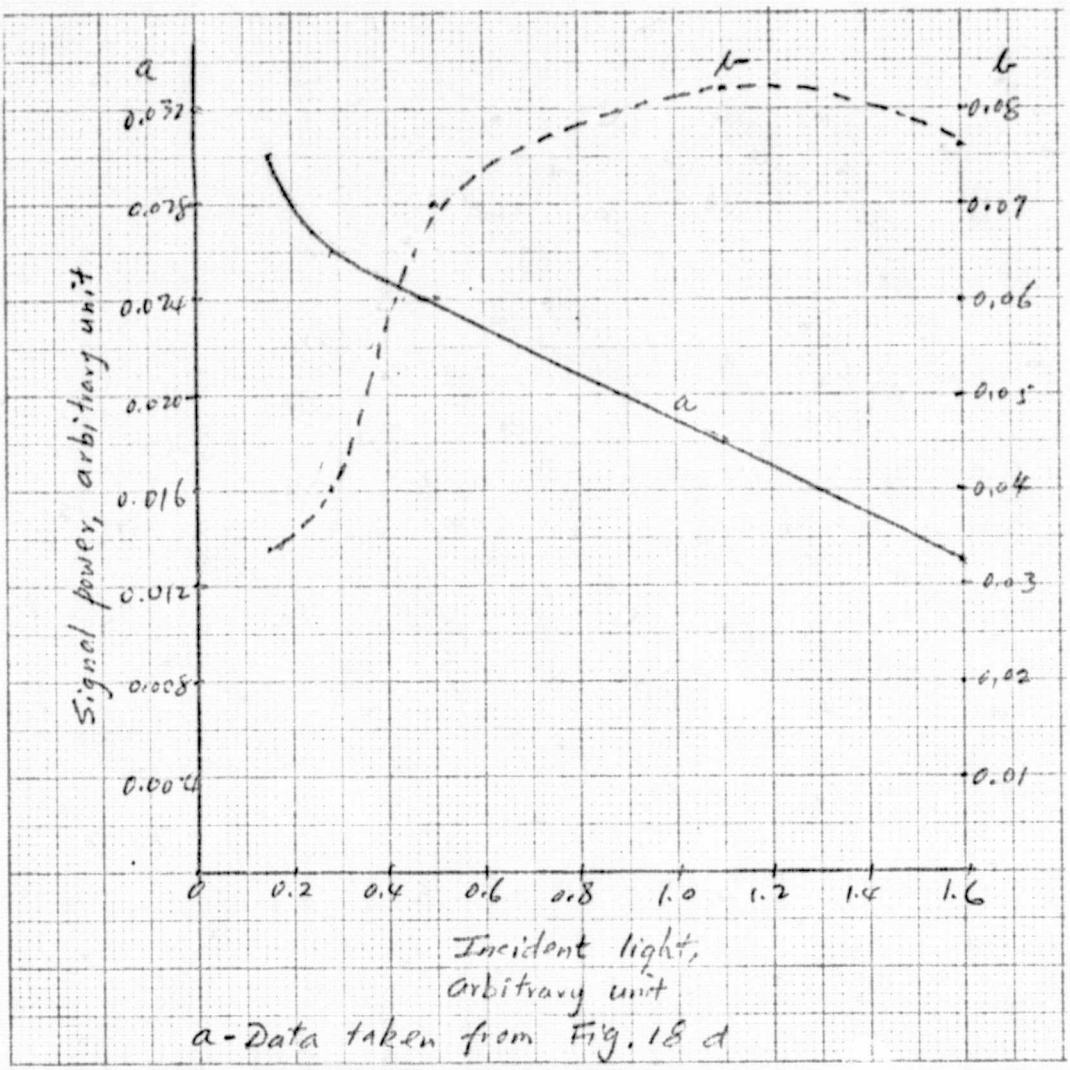
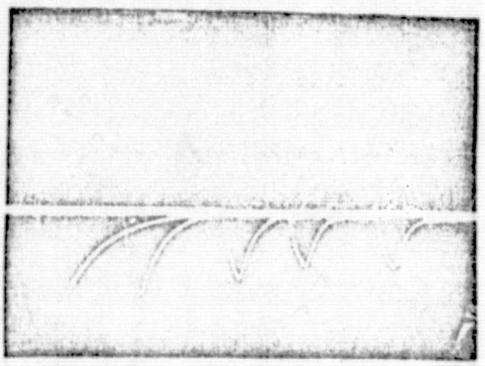


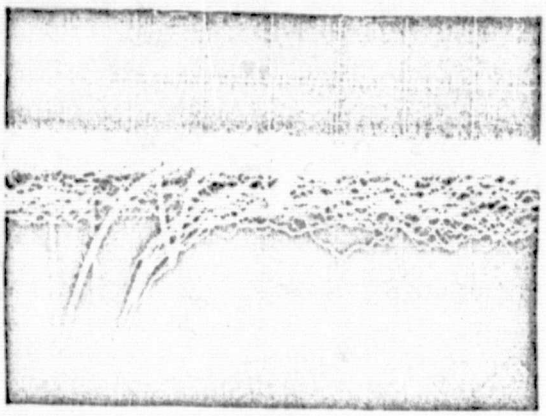
Fig. 15 a, BTW signal



scale = 0.005 V/cm

Cr8 laser pump attenuated by filters

→ increasing pump
11, 20, 25, 30, 33 dmp



scale = 0.005 V/cm

Cr8 laser pump not attenuated

→ increasing pump
0, 11, 13, 15, 20, 25

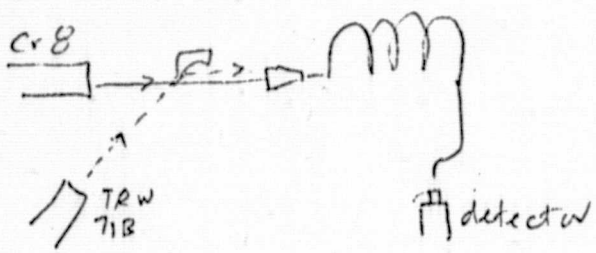


Fig. 16

EXPERIMENTS USING TWO ARGON LASERS (PART II)

The low power TRW laser was steered and focused as signal into one end of the fiber while the Cr 8 high power laser pump was fed into the other end by the microscope objective as shown in Fig. 17. Results of the transmission experiments are given in Fig. 18. Signal amplification was also possible on the same setup as seen in Fig. 19.

To avoid heating of the fiber by the intense pump the beam was chopped and the experiments repeated. Signal amplification was again observed as demonstrated in Fig. 20.

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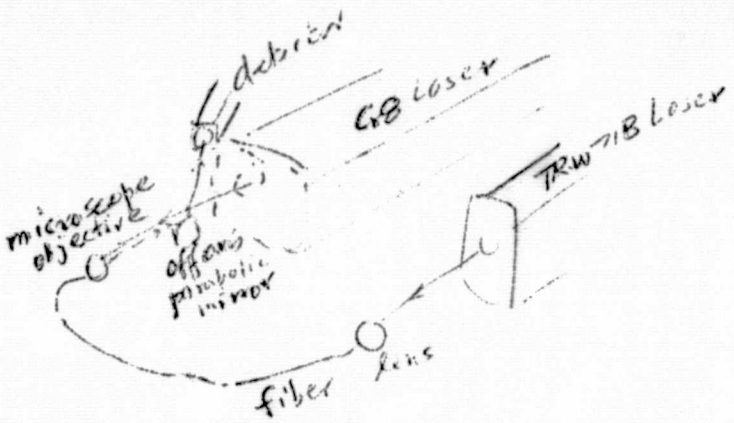

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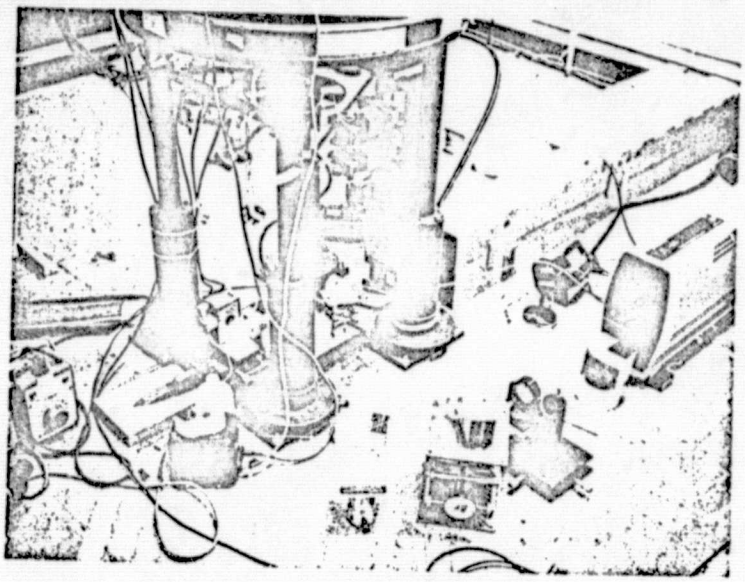

Fig. 17

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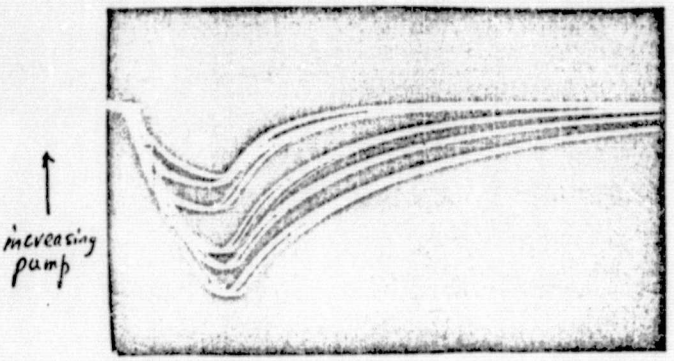
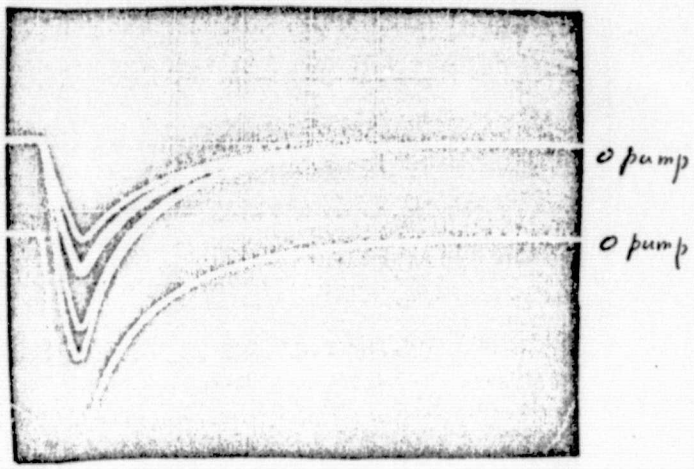
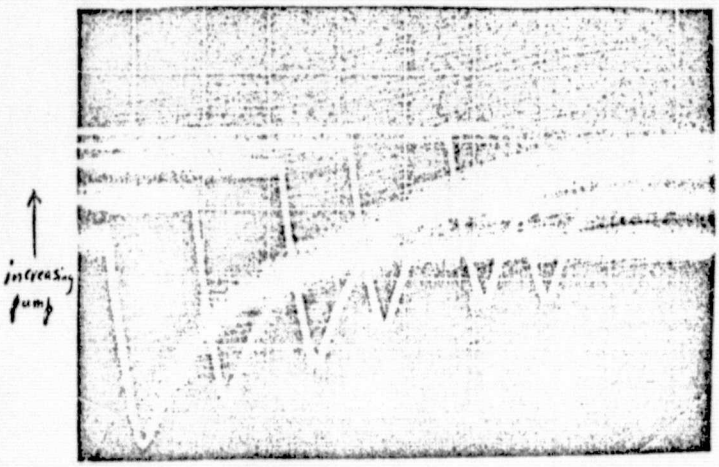


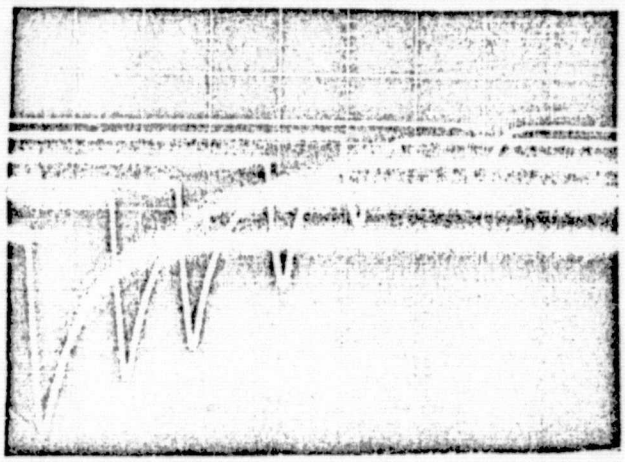
a. scale: 0.02 v/cm



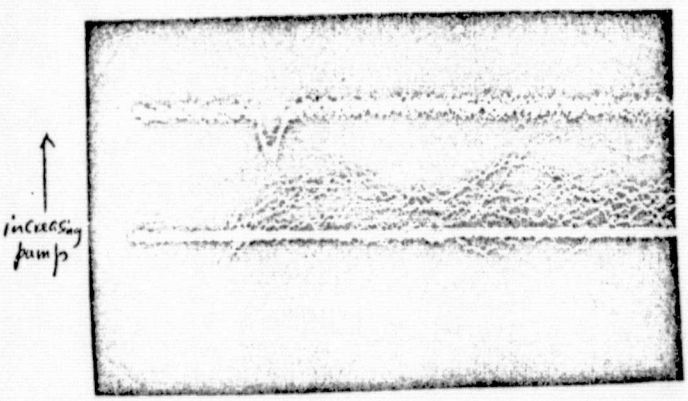
b. scale: 0.02 V/cm



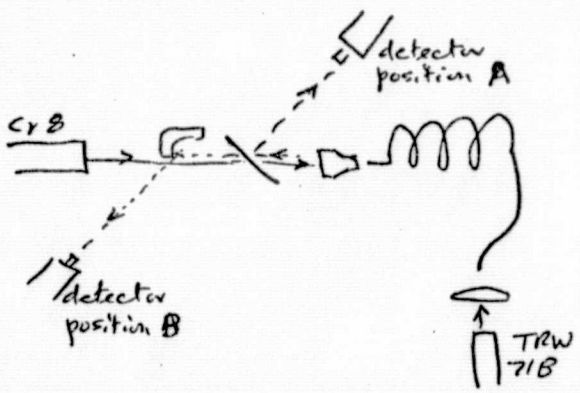
c. scale: 0.02 v/cm



d. scale: 0.01 V/cm



e. scale: 0.01 V/cm

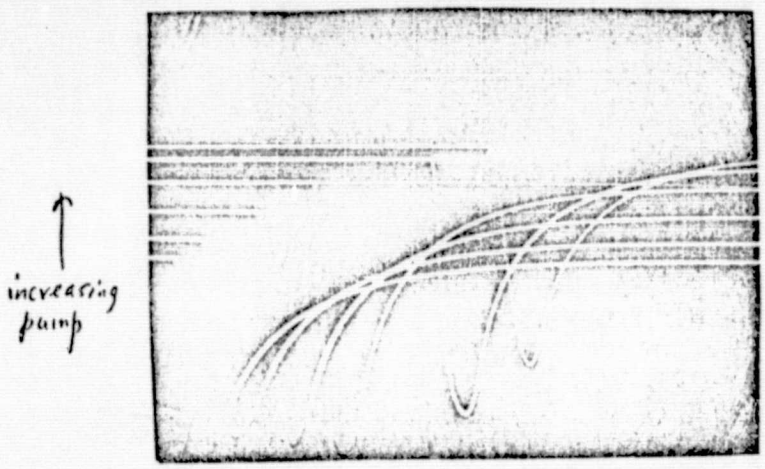


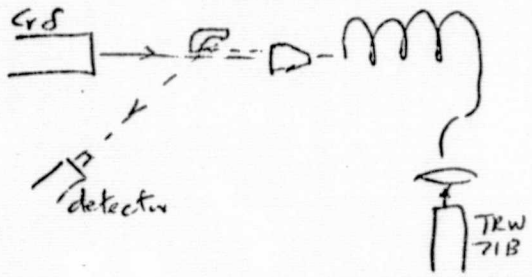
d - taken at detector position A

a, b, c, e - taken at detector position B. d, e - 2 laser beams almost coincide completely
one end of fiber burned

increasing pump - 11, 16, 20, 25, 30, 33 amp

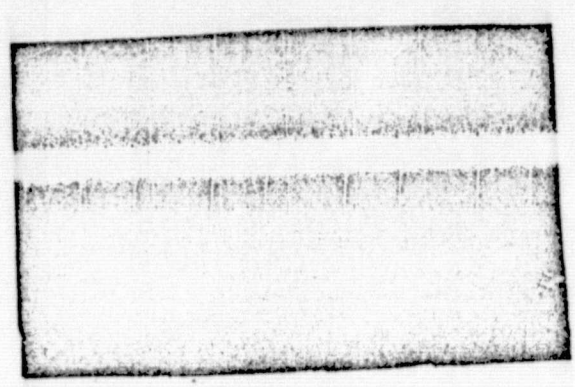
Fig. 18 Detected signal (BTW)



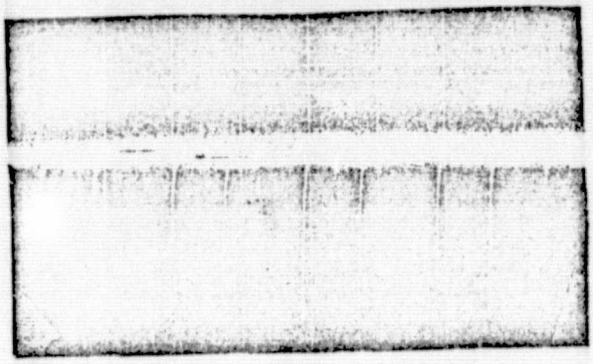


increasing pump - 11, 16, 20, 25, 30, 33 amp

Fig. 19. Detected BTW signal



a.



b

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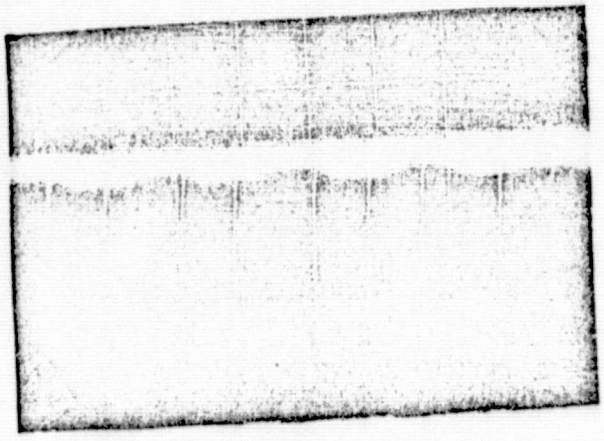
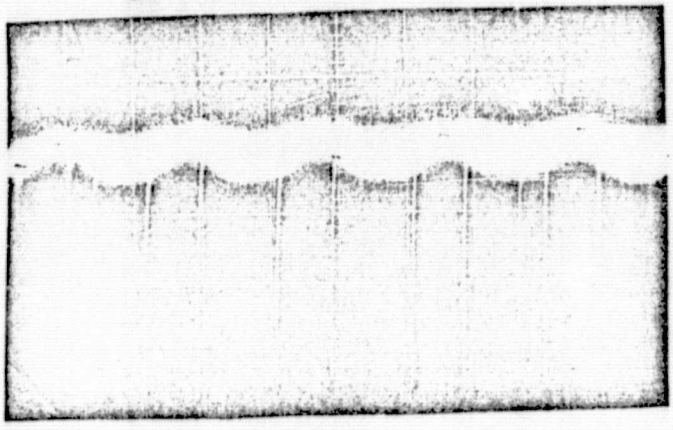
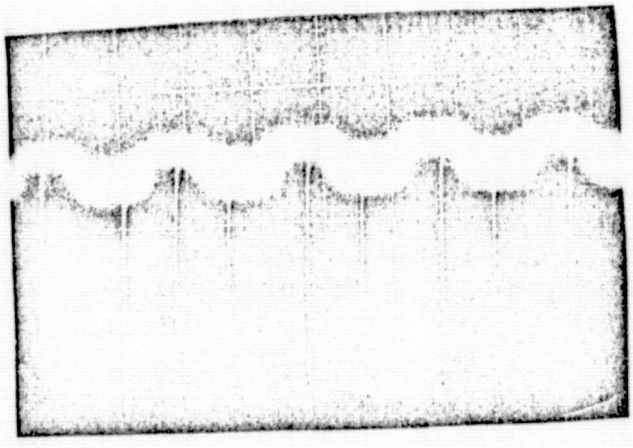


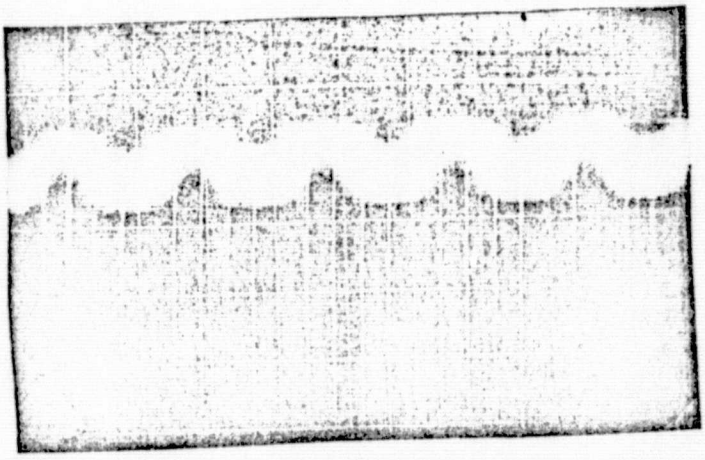
c



d



e



f

Scale: 0.005 V/cm

a : b : c : d : e : f
11 : 16 : 20 : 25 : 30 : 33 Amp

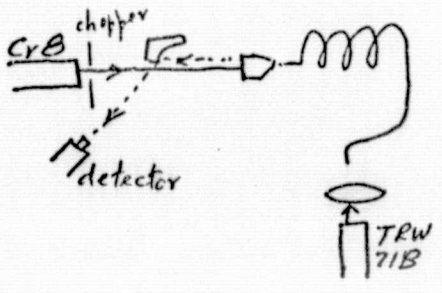


Fig. 20. Detected signal pulse and chopped pump

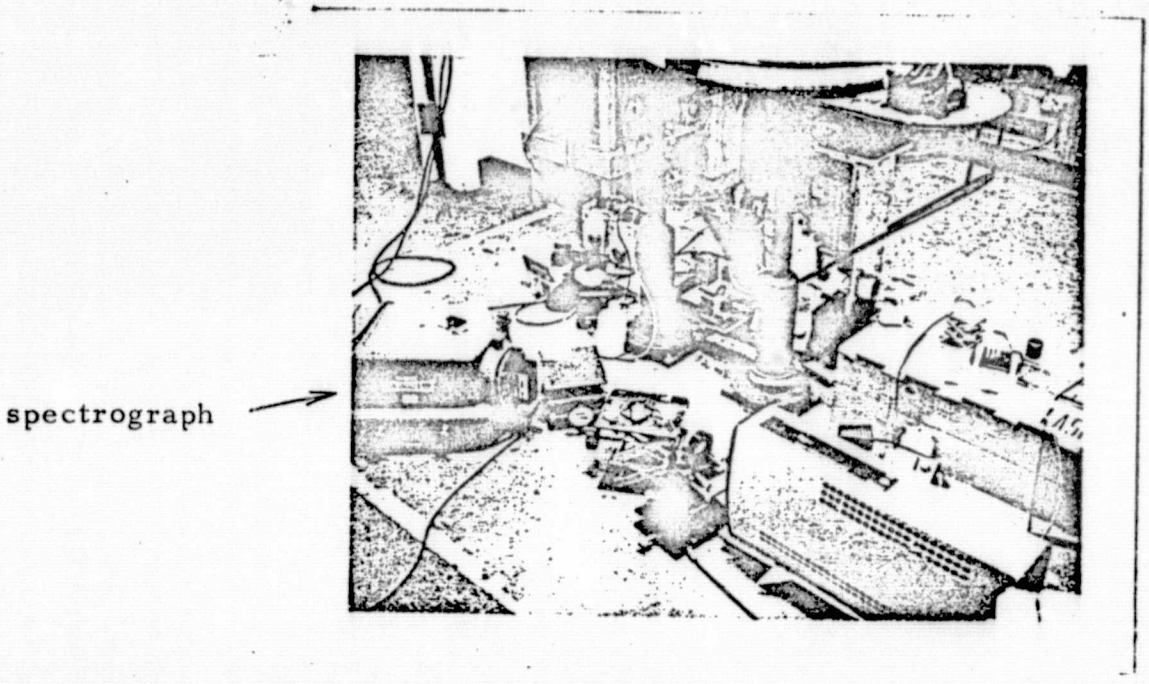
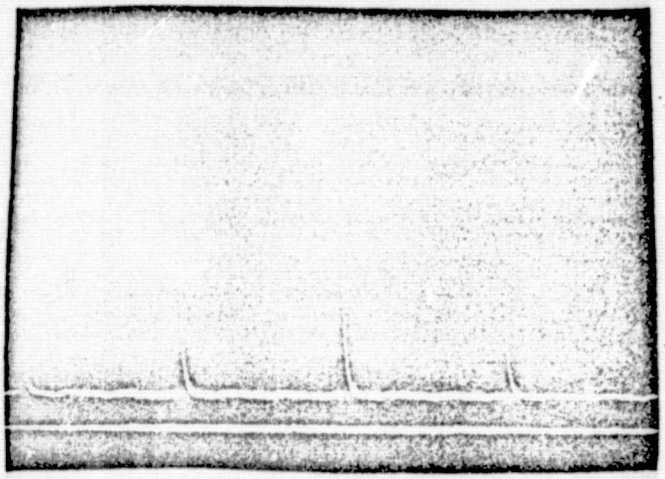


Fig. 21

Footnote: Same setup as in Fig. 17 with addition of a spectrograph and photomultiplier in place of detector



Scale: 0.1 v/cm

Lower trace: input signal from TRW 71B laser,
Upper trace: input signal at the instant when the Cr 8 laser pump is turned off. The level eventually decays to that of the lower trace.

This is the signal from the photomultiplier at the exit slit of the monochromator set at 5145 Å.

Note: When the monochromator is set at 5017 Å the pump has no effect on the input signal (at 5017 Å).

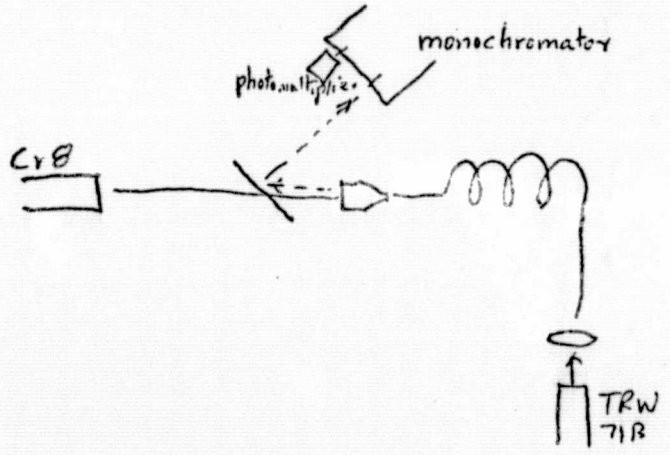


Fig. 22

SPECTROGRAPHIC STUDIES OF LASER PUMP AND ITS TRANSMISSION THROUGH A FIBER

The spectral profile of the incident Cr 8 laser pump and its transmitted light through the fiber was recorded. Figure 23 gives the pump line at the fiber exit end, which was placed immediately adjacent to the entrance slit of a spectrograph. The photomultiplier at the exit slit was saturated as expected since we only intended to uncover the tails of the line to look for Raman peaks. A weak peak was observed at 5312 Å. The fine structure of the line close to line center was also revealed with the fiber end positioned away from the entrance slit (see Fig. 24). A number of beam splitters were then used to reduce the light level of the pump to be detected so that the photomultiplier would not be saturated. Figure 25 shows the true line shapes together with the distorted profiles with saturation.

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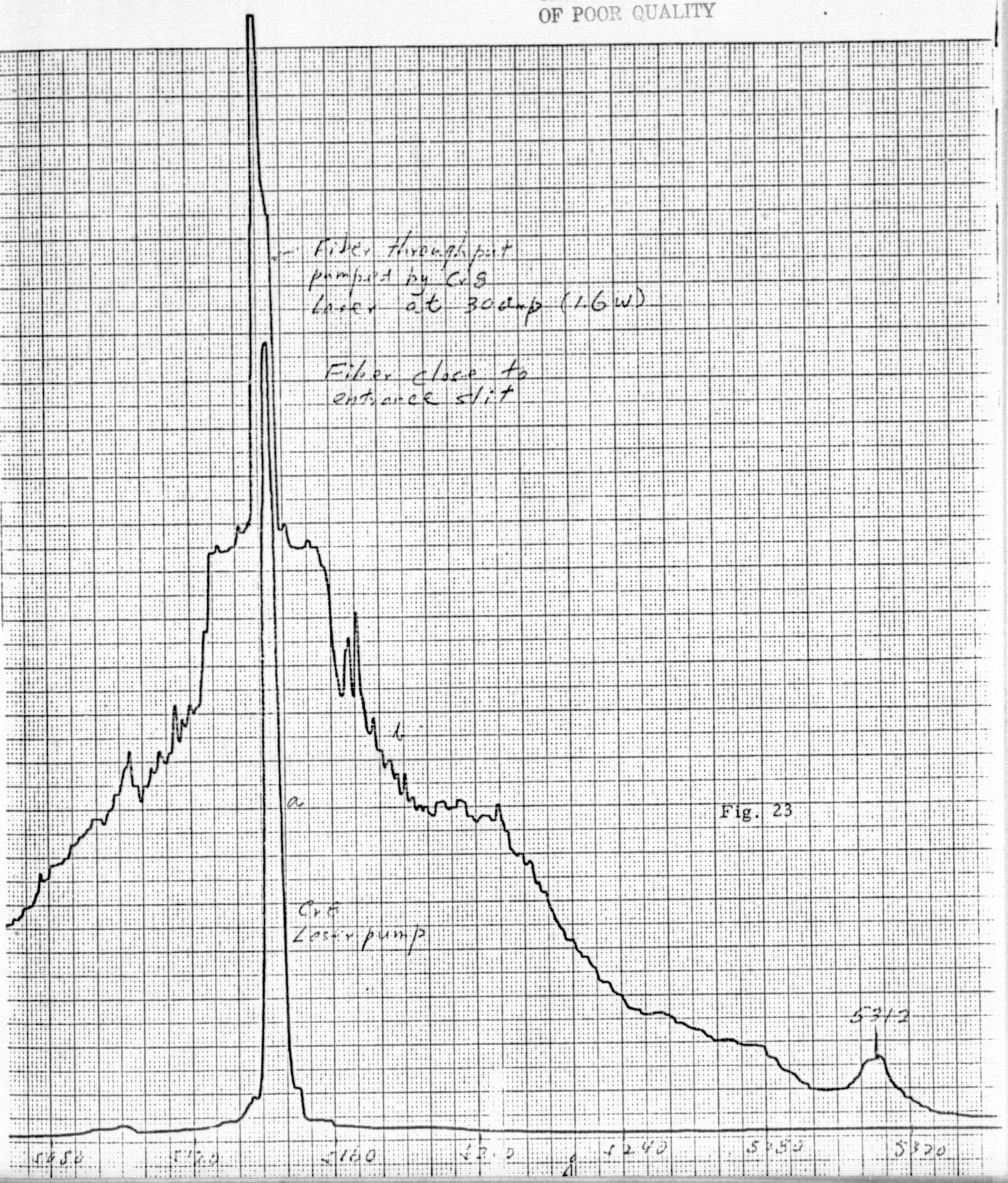

Fig. 23

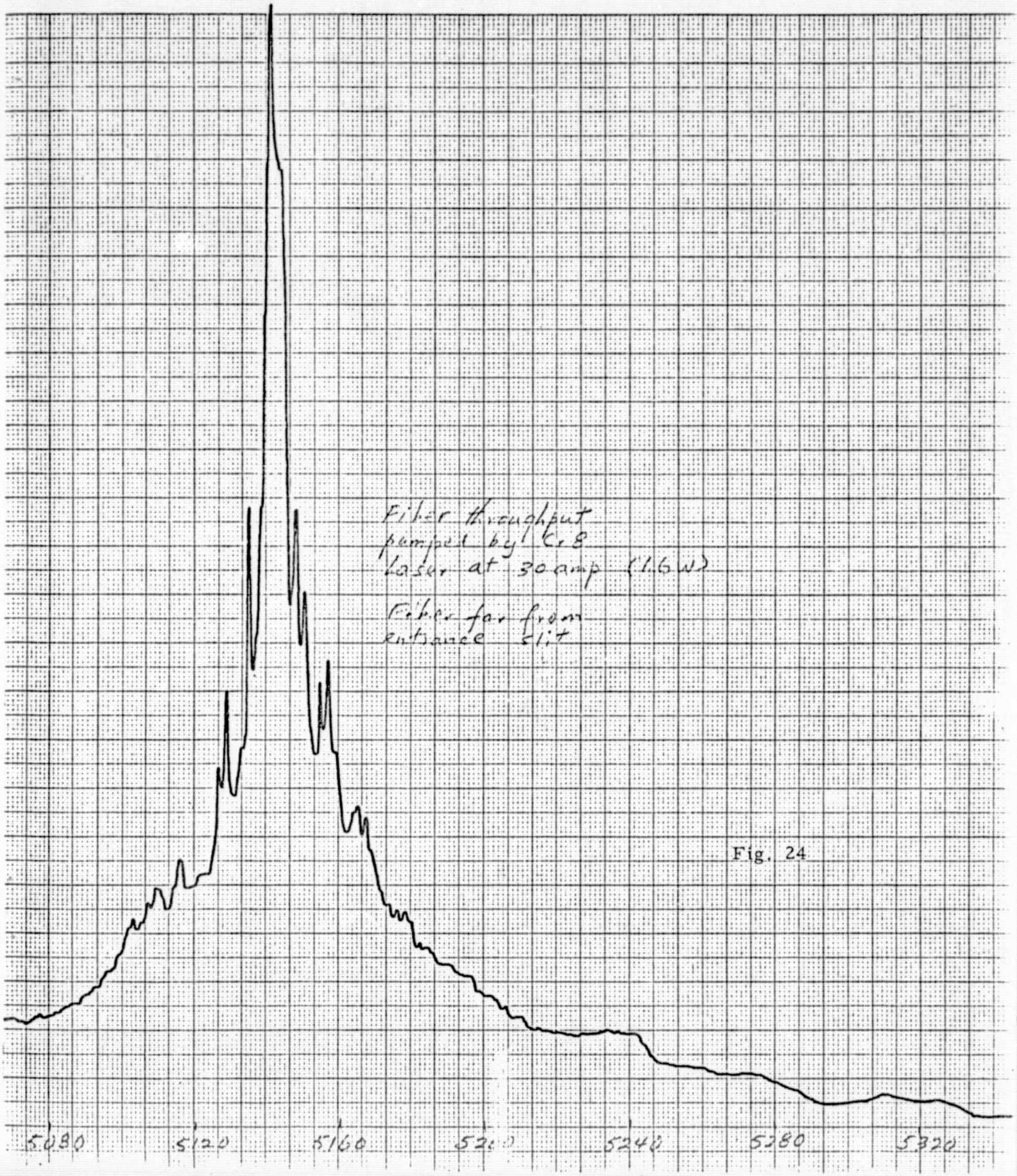
Fiber throughput
pumped by Cr:8
laser at 30 amp (1.6W)
Fiber far from
entrance slit
5080
5120
5160
5240
5280
5320

Fig. 24

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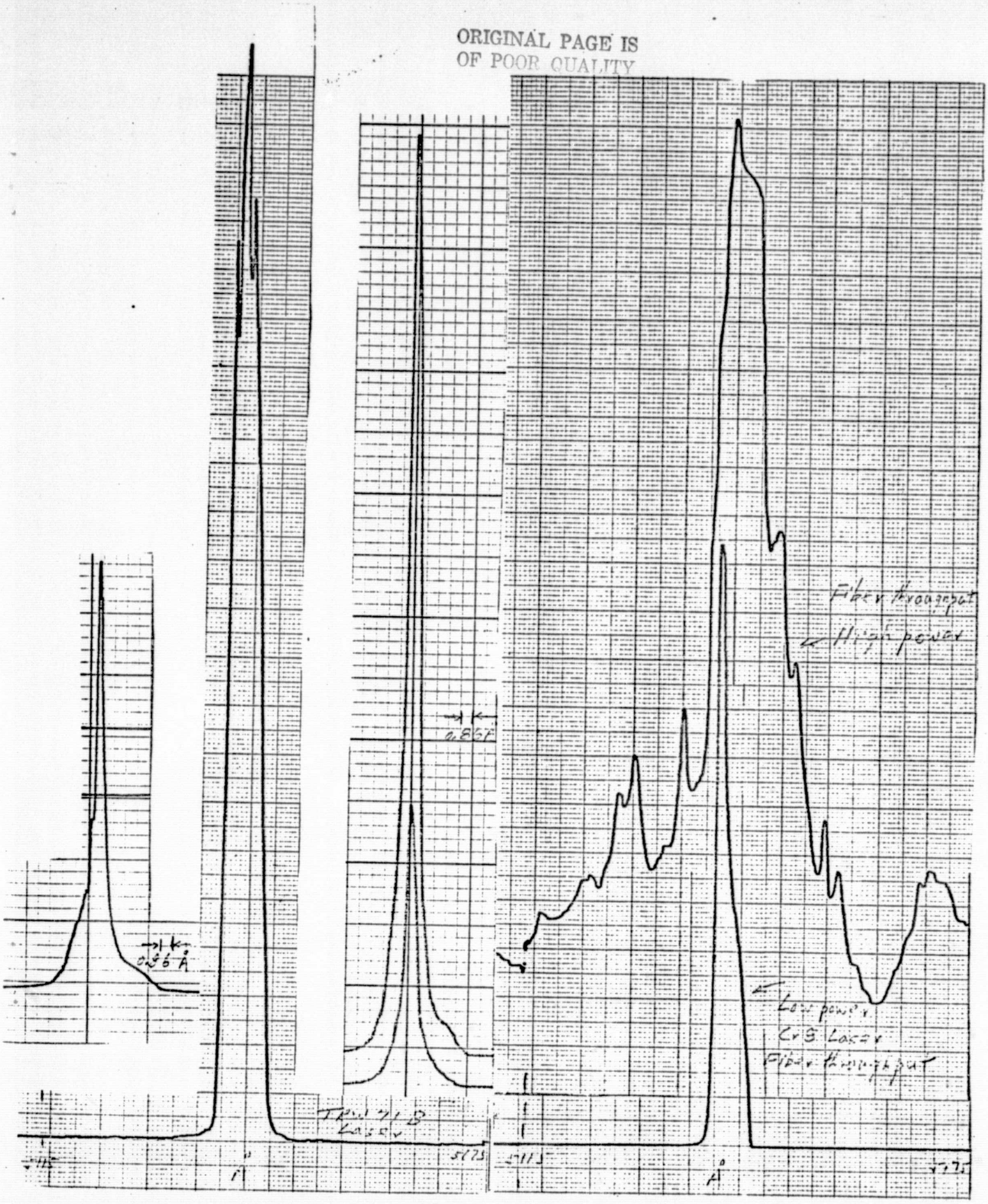

Fig. 25

GENERAL DISCUSSION OF RESULTS

a. Laser Pump Transmission (Fig. 8)

Since great care has been taken not to saturate the detector, this set of data on laser transmission should be accurate. Pump depletion is thus confirmed. However, when the pump values are normalized to the theoretical threshold of $\pi/2$ and plotted in Fig. 26, our data on the argon laser deviate appreciably from our proposed theory.

From measured spectral profile of the argon laser pump we doubt that SRS took place. According to the Raman gain profile in Fig. 27, the Raman shift should be maximum at approximately 300 - 400 cm^{-1} from the pump line center. Only a weak peak appeared at 5312 Å. The SBS process is thus suspected.

To clarify this point, a low power argon laser lasing multi-lines was used as a signal. We consistently found the strongest effect of the pump on the 5145 Å signal line.

b. Signal and Pump Interactions

Only qualitative results are given here. Depletion of the signal or the so called up-conversion was observed in Fig. 15 a for a FTW signal. Due to severe masking of the signal by the intense pump, we believe there was excessive saturation of the detector. Although only the pulsed signal was observed, both signal and the cw pump light was incident on the detector. By attenuating both signal and pump with filters, signal depletion was again observed in Fig. 16 a. Depletion was significantly less (see Fig. 15, curve b). Depending on the alignment between the pump and the signal waves we also observed amplification of the FTW signal at low pump and then depletion of the signal at higher pump values as seen in Fig. 16 b. These variations are plotted in Fig. 15 a for the BTW signal case. In the latter case, such variations are more pronounced.

The strong effect of the pump on the 5145 Å signal line was clearly seen in Fig. 22. Here, the small input signal was greatly amplified (more so with higher pump), but was observed only after the pump light was

turned off. A possible explanation was that the intense pump saturated the photomultiplier at the exit slit of the spectrograph so that amplification effect was not obvious under intense pump light illumination. But when the pump light was removed the photomultiplier was able to relax .

Our experiments using the dye laser and the argon lasers described above give a clear indication of the existence of stimulated Brillouin scattering at pump levels of the order of a watt. Work will be continuing at higher pumps. Slight surface damage was also observed at the 1.6 W level.

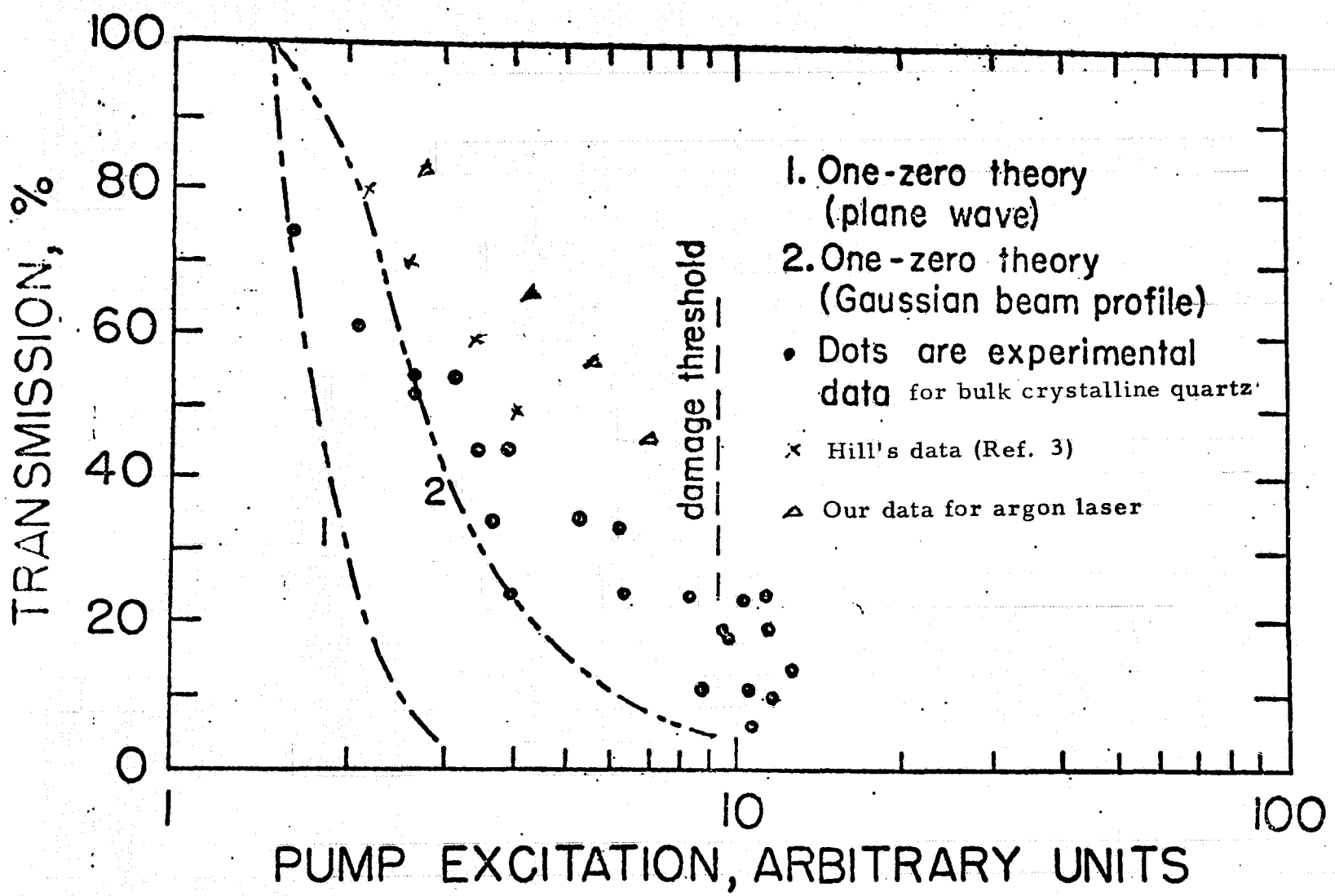
100
80
60
40
20
0
TRANSMISSION, %
1
10
100
PUMP EXCITATION, ARBITRARY UNITS
damage threshold
1
2
1. One-zero theory (plane wave)
2. One-zero theory (Gaussian beam profile)
• Dots are experimental data for bulk crystalline quartz
× Hill's data (Ref. 3)
△ Our data for argon laser

Fig. 26

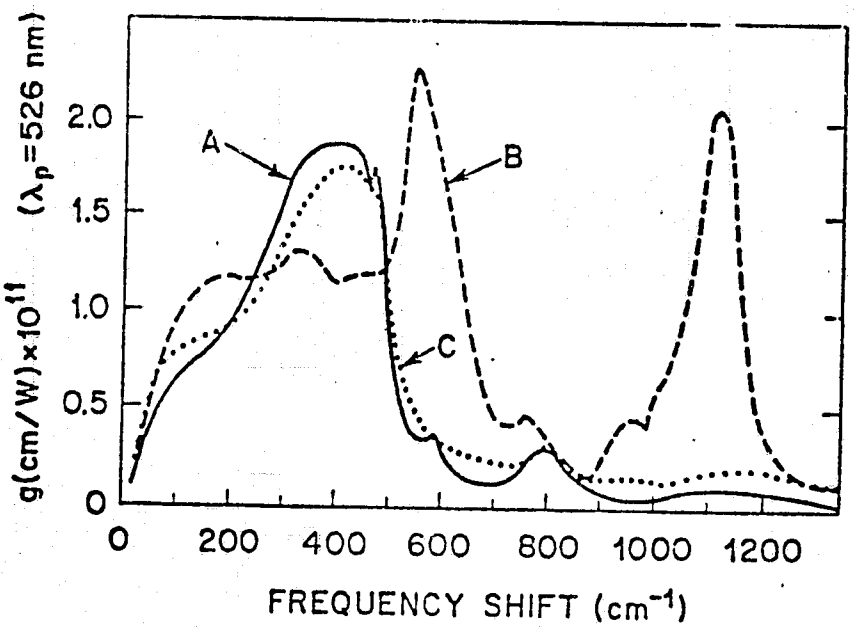

Fig. 27. *Raman gain curves for (A) fused quartz, (B) soda-lime silicate (20:10:70), (C) Pyrex. Gain deduced from spontaneous scattering measurements.*

REFERENCES

[1] H. Hsuand C. Yu, Appl. Phys. Lett. 22, 41 (1973).

[2] R. G. Smith, Appl. Opt. 11, 2489 (1972).

[3] K. O. Hill, B. S. Kawaski and D. C. Johnson, Appl. Phys. Lett. 28, 608 (1976).

[4] H. Hsu and C. Yu, Proc. IEEE (Lett.) 64, 1638 (1976).

[5] E. P. Ippen and R. H. Stolen, Appl. Phys. Lett. 21, 539 (1972).

[6] K. O. Hill, D. C. Johnson, and B. S. Kawasaki, Appl. Phys. Lett. 29, 185 (1976).

[7] C. Yu and S. A. Byers, Faculty Review, North Carolina A&T State University, Greensboro, NC (1976).

[8] C. Yu, M. Haw and H. Hsu, Elect. Lett. 13, 240 (1977).